MUNRO'S MODERN NAVIGATIONAL AIDS

BY
CAPT. G. E. EARL Extra Master
AND
CAPT. G. C. BOYLAN, M.B.E.

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MUNRO'S
MODERN
NAVIGATIONAL AIDS

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OF SOUTH SHIELDS MARINE AND TECHNICAL COLLEGE

GLASGOW, C.2:

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PREFACE

WE OFFER THIS TEXT HUMBLY, not as electronic experts but as seamen and teachers.

Our aim has been limited. We have attempted to state simply and briefly sufficient of the principles of some modern navigational aids to enable candidates to pass the Ministry of Transport Examinations. The text is not meant to be a complete statement, nor in any way to replace more specialised works, or the various maintenance manuals.

Our thanks are due to :—

Messrs Sperry Gyroscope Co., Ltd.
Messrs S. G. Brown & Co., Ltd.
Messrs Kelvin Hughes & Co.
Messrs Marconi International Marine Communications Co., Ltd.

Our colleagues on the staff of the South Shields Marine and Technical College, and to all who have assisted directly, or indirectly, with the work.

G.E.E.
C.C.B.

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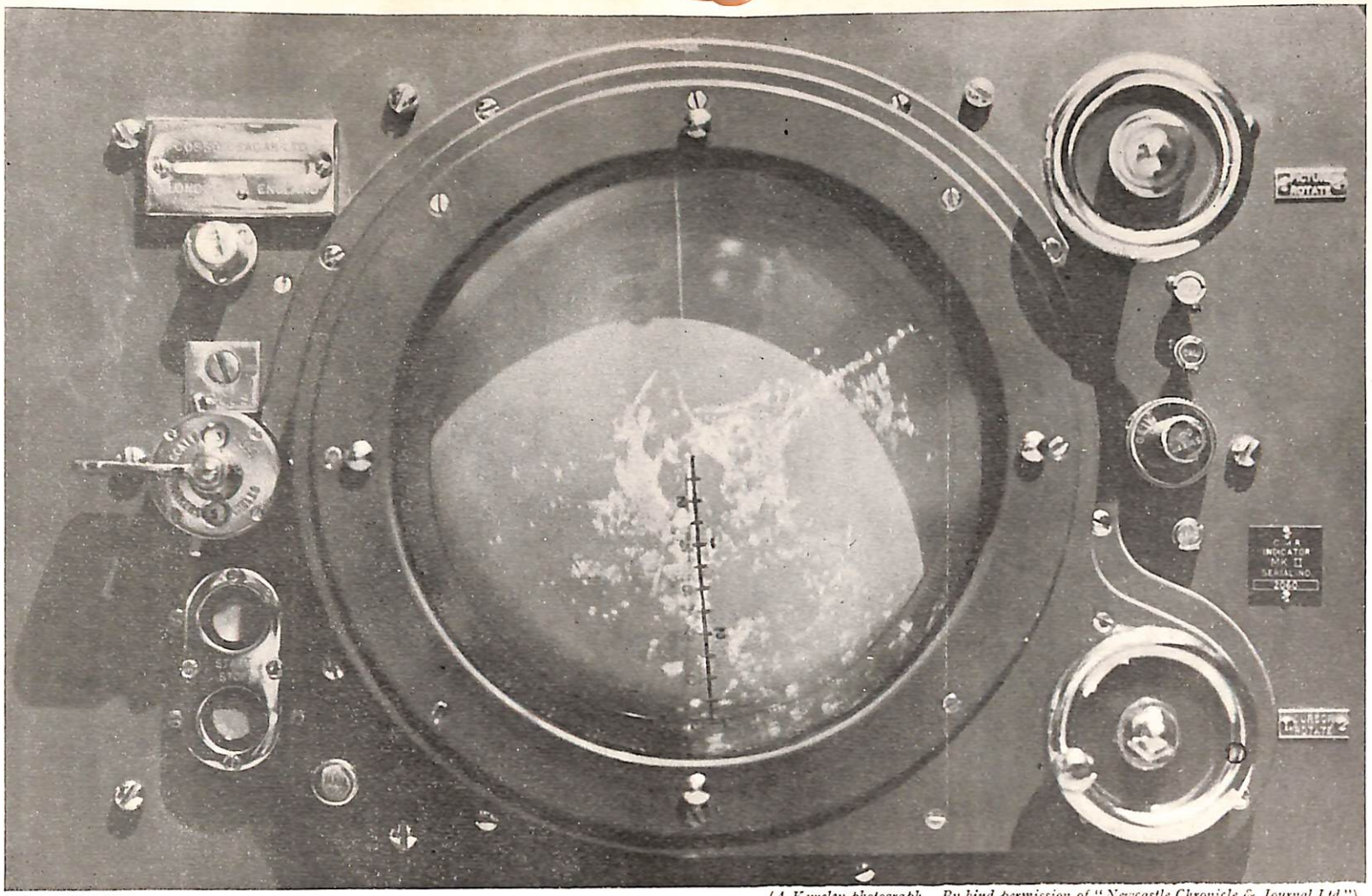

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DISPLAY PANEL OF COSSOR RADAR SET AT SOUTH SHIELDS MARINE AND TECHNICAL COLLEGE RADAR STATION.

CHAPTER I.

THE GYRO COMPASS—FUNDAMENTALS

1. The gyroscope.—A gyroscope is a spinning wheel mounted with three degrees of freedom. That is, it is free to turn about three axes mutually at right angles to each other. See Fig. 1.

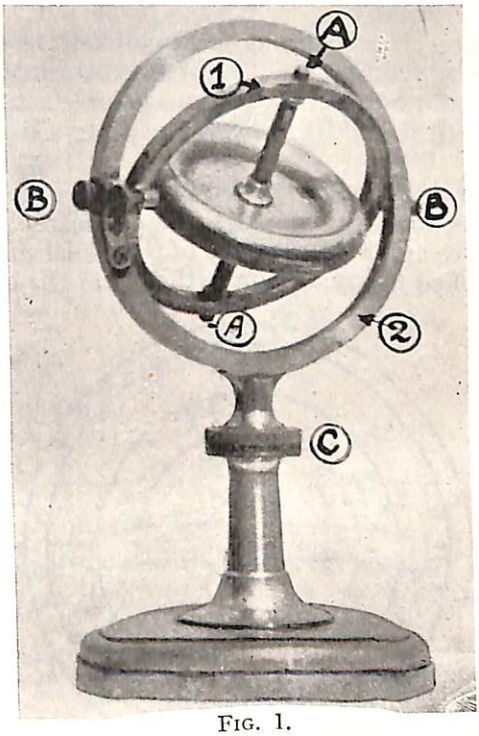


FIG. 1.

The wheel spins on the axle A which is mounted inside the ring (1). In the gyro compass the spinning wheel (rotor) is completely enclosed in the rotor case.

The rotor case is pivoted at BB inside a vertical ring (2). Both axles A and BB are horizontal but they are at right angles to each other. In the gyro compass, since the axle A points North and South BB are called the East-West bearings, or horizontal case bearings.

The vertical ring (2) is pivoted about the vertical axis (C).

2. Inertia.—A wheel mounted in this way will exhibit the property of " gyroscopic inertia " and the spinning wheel will keep its axis in the same direction in space irrespective of movements of the base. Note that we say in the same direction *in space*.

This property is the outcome of a law in mechanics known as the law of the conservation of angular momentum. Angular momentum is angular velocity $\times$ moment of inertia.

If a body is moving in a straight line, say due East, a force applied from the South would deflect it from its path and make it travel, not North, but a little N. of E. The faster the body is travelling in the first place the smaller the resultant deflection will be.

If our spinning wheel is spinning very fast a force applied to it will deflect it but slightly, especially if all three axes are made as near frictionless as possible and then very little force can be transmitted to the wheel. If such a wheel has no friction, no control system, and is suject to no external torques, it is called a "free gyro."

3. Precession.—The second property of our free gyroscope is, at first glance, even more remarkable. If we exert a force on the wheel, the wheel will not turn around the axis of the applied force, nor will the rate of spin be affected, but it will turn about the other axis. This movement is called precession.

In fact if any turning force is applied to the free gyroscope the spinning wheel will turn so as to bring the axis of spin nearer to the axis of the applied force. A force applied to the rim of the wheel will therefore behave as if it had been applied 90° in advance (that is in the direction of spin).

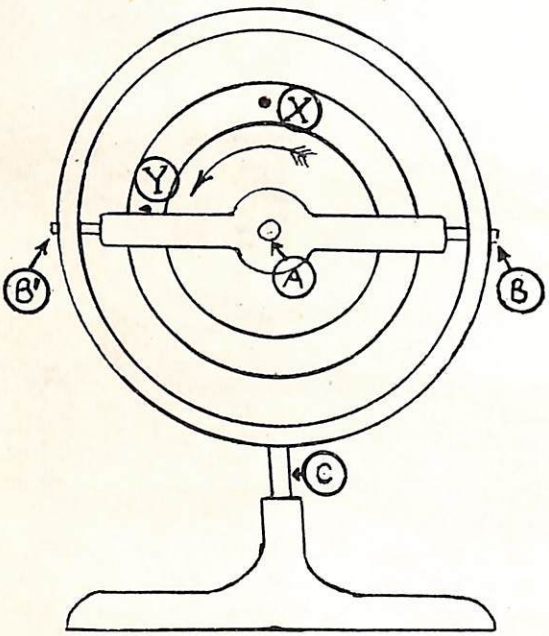


FIG. 2.

If the wheel was not spinning and we pressed in at X (Fig. 2) the end of the axis A would move up, and the wheel would tilt about BB'. If the wheel is spinning as shown then pressing on X will act like a press on Y and the end of the horizontal axis B will move out of the paper and B' move into the paper—the wheel will turn on the vertical axis C. The wheel tries to set its direction of spin in line with the direction of the applied force.

Similarly in Fig. 3 if the wheel is not spinning a press at X will make it turn on the vertical axis C, but if the wheel is spinning then a push at X behaves like a push at Y and the end A will lift up and the wheel will tilt on the axle BB^1.

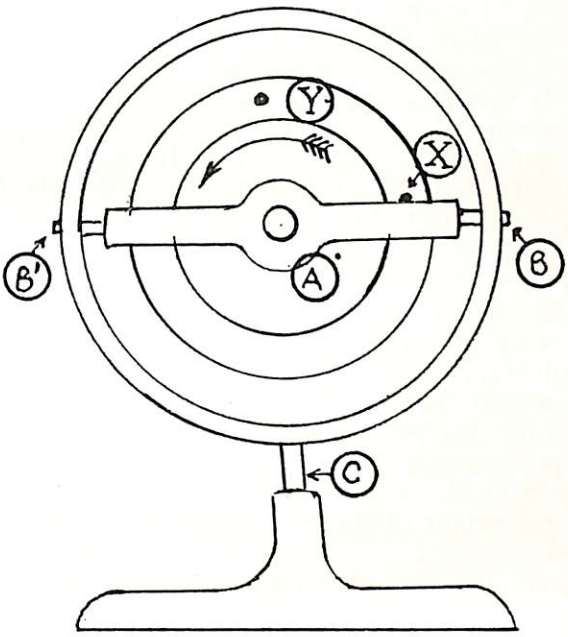


FIG. 3.

The effect of precession is also the outcome of " the law of the conservation of angular momentum " but we may explain it by the triangle of forces.

The forces involved are turning forces (torques) and if we wish to represent these by straight lines we must use some convention. The

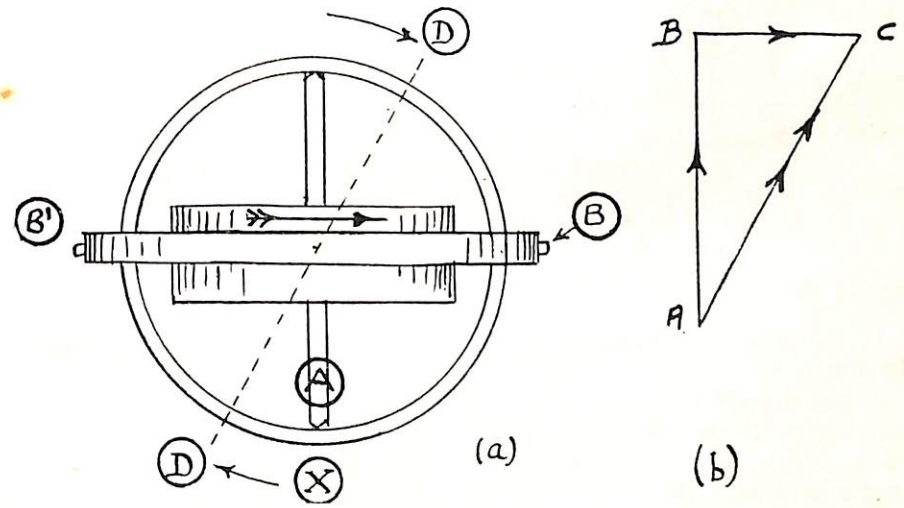


FIG. 4.

usual convention is the "right-hand screw" convention in which we represent a torque by a straight line running in the direction in which a right-handed screw would be driven by such a turning movement. In Fig. 4 we see the wheel looking vertically down on it. The torque necessary to spin the wheel as shewn would drive a right-hand screw up the page and is represented by the line AB. Pushing at X (into the paper) produces a torque which would drive a screw to the right and is represented by the line BC. Both torques together give the line AC which represents a torque about the axis DD (shown dotted). The end A will move to the left which agrees with the rule stated above. It should be noted that the push on X is the same as pushing the lower edge of the wheel up the page.

Note that any attempt to turn the rotor (on axis C) will only cause it to tilt (on BB^1). Any attempt to tilt it (on BB^1) will make it turn (on C). This property enables us to maintain balance on a bicycle. If we are falling over an attempt to turn the steering wheel will tilt us upright. Roll a penny down a gentle slope, note if you touch the top with a piece of folded paper it will turn. If you try to steer it then it will lean over. If it leans over its weight tries to tilt it further over and makes it turn. Patience is needed for this but it is worth the bother.

The rate of precession is directly proportional to the applied couple and varies inversely as the angular momentum of spin, which depends upon the speed and weight of the wheel, and the manner in which the weight is disposed.

(An orange and a little imagination will be useful for the next part).

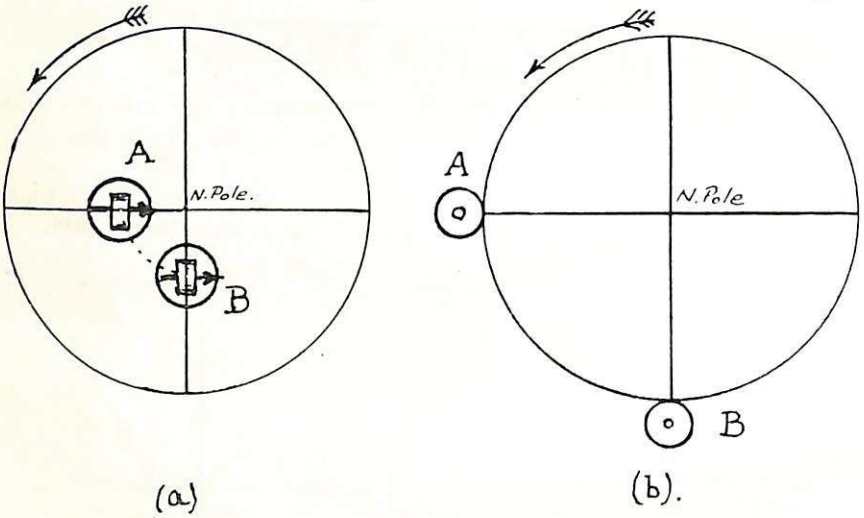


FIG. 5.

4. Turntable effect.—If we could keep our wheel spinning continuously and if we refrained from touching it then it would keep its axis (A) in the same direction in space, but this is not necessarily the same direction in relation to the earth for the earth is rotating.

Fig. 5 is a picture of the earth looking down on the N. pole, if we started a gyro at A (in a high latitude) pointing North and horizontal—in space that is pointing towards the right—six hours later the rotation of

the earth will have brought the gyro to B and it will still be pointing to the right but this is no longer North—it is East. This effect is called " the turntable effect." If the gyro had been on the equator (Fig. 5b) then when it is pointing North it is pointing straight out of the paper (at A) and six hours later it is carried round to B and is still pointing straight out of the paper that is—still North.

Therefore :—In N. Hemisphere the N. end swings East.
In S. Hemisphere the N. end swings West.

(Figure that out for yourself).

The effect is maximum at the Pole and nil at the equator.

The effect is maximum on North and South and nil on E. and W.

The rate of change of azimuth of a free gyroscope, due to " turntable effect " is $= 15° \times$ sine latitude if axis is horizontal.

In latitude 45° it will be :—

$15° \times \sin 45° = 15° \times \cdot 707 = 10°\cdot 6$ per hour.

This apparent movement of the axis is often called " drift."

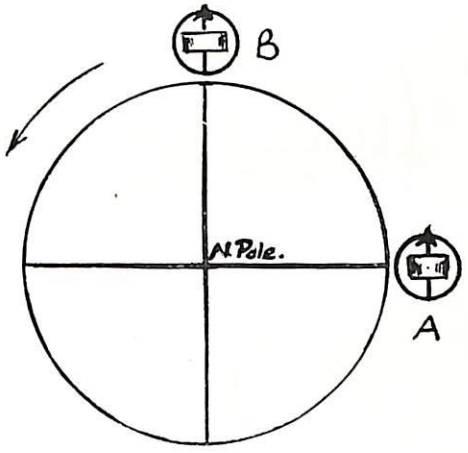


FIG. 6.

5. Tilt effect.—Suppose in Fig. 6 we start a gyro with its axis horizontal and pointing East (at A) that is it is pointing up the page. Six hours later the gyro will be at B and will still be pointing up the page, but this is now pointing vertically upwards (not East).

Tilt effect always causes the end towards the East to lift up. It is maximum on the equator and nil at the Poles. It is maximum on E. and W. and nil on N. and S.

The rate of tilt is $= 15° \times$ cosine latitude $\times$ sine azimuth per hour. In latitude 50° heading East it will be :—

$15° \times \cos 50° \times \sin 90° = 15° \times \cdot 643 \times 1\cdot 0 = 9°\cdot 6$ per hour.

6. Together.—Turntable and tilt effects take place together. If we start the free gyro horizontal and axis pointing North in middle latitudes then we are pointing at an imaginary fixed star which is on the meridian below the Pole. Such a star will move Eastwards (drift) and up (tilt).

The azimuth of the gyro will be the azimuth of the star and the tilt of the gyro will indicate the altitude of the star.

If we know the heading of a free gyro, its tilt and the latitude at any instant then the haversine formula will enable us to find the declination of the imaginary star to which it is pointing, and with the sine rule we can find its L.H.A. At some later time, since we know the new value of L.H.A., the declination and the latitude, we can calculate the azimuth, which will be the heading of the gyro and the altitude will be equal to the tilt.

7. The pendulous gyro.—A simple gyroscope then is no good as a compass, if we start it North it will very soon not be North. For a compass we must arrange things so that the gyro has a North-seeking property.

Suppose we fix a weight (a bail) as in Fig. 7 by attaching arms rigidly to the rotor case.

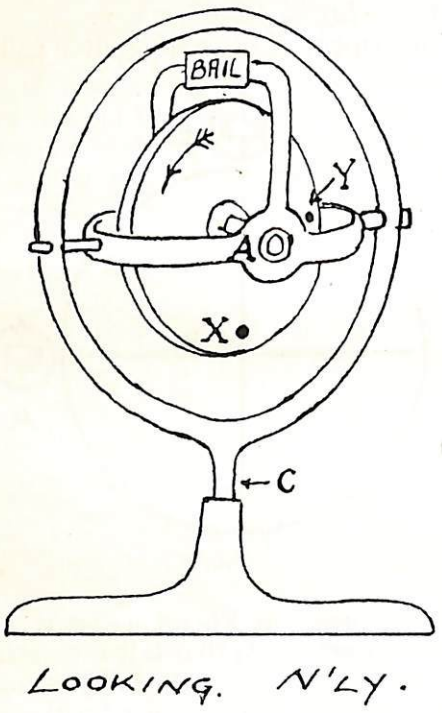


FIG. 7.

If the gyro axis is horizontal the bail will have no effect, but, if the axis tilts, the bail will push down on the low end of the axis. If A tilts down, the bail will try to push down on the low end of the axis. If A tilts down, the bail will try to push A farther down—this is like a push in at X but because of precession it will behave like a push at Y and instead of A moving farther down it will move to the right (rotating about C). Now suppose we start the gyro (with its bail) with the axis North and horizontal. In the N. hemisphere turntable effect swings the N. end East. As soon as the N. end is to the East, tilt effect will tilt it up. The bail (moving out of

the paper in Fig. 7) will press down on A. This is a push in at X and will behave like a push in at Y, A will move to the right and the N. end will swing back towards the meridian.

Suppose we had not started the gyro N., but suppose it had been a little West of North. Now tilt effect lifts the East end up, and since A (the S. end) is a little to the East, then it will lift up. This will move the bail into the paper, and will cause a push up (out of the paper) at X which will behave like a push out of the paper at Y. The S. end will move West, and the N. end will come back towards the meridian. We have made the gyro North-seeking.

We must not rejoice too soon, let us consider the movement a little further.

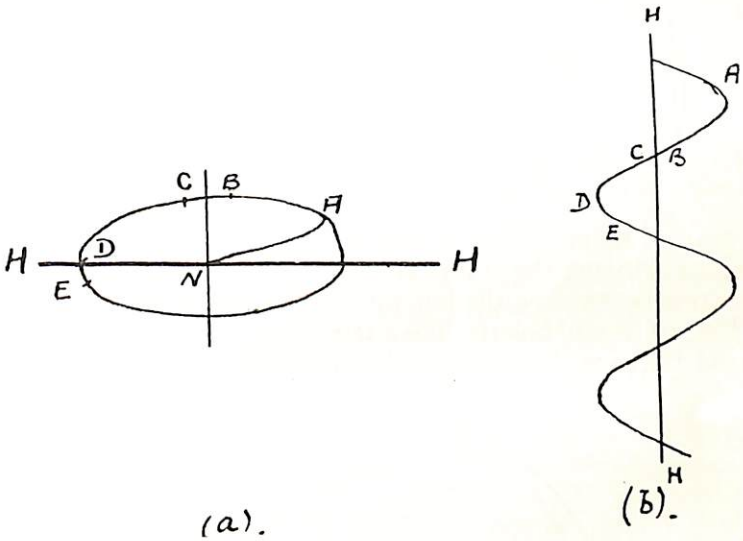


FIG. 8.

In Fig. 8 (a) suppose HH is the horizon. If we start the gyro with its axle horizontal and pointing N., it will be pointing at N. Turntable and tilt effects will swing it East and up (to A). The bail will take effect and start it moving back towards the meridian, but so long as the N. end is East it will continue to tilt up. The gyro will reach the meridian with the N. end tilted will up (at B) and because of the tilt the N. end will continue to swing West (to C). As soon as the N. end is to the West of the meridian tilt effect will start putting the N. end down, and it will become horizontal (at D). Because it is West it will continue to move down, below the horizontal (E) and the bail will now start swinging it back towards the meridian again.

The compass then will not settle on North but will wander back and forth as in Fig. 8 (b). This is called an undamped curve.

8. Damping.—We must remedy this state of affairs and arrange to get a damped curve. That is one where the amplitude gets less at each half swing, Fig. 9 (a).

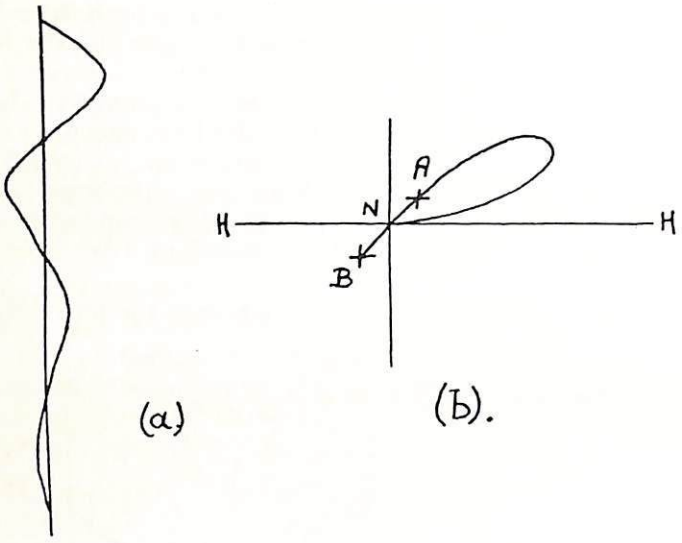


FIG. 9.

One way of doing this is to arrange the bail so that it takes out the tilt as well as bringing the compass back to the meridian, Fig. 9 (b).

If we contrive to have the bail push at a point which is East of vertical (at X in Fig. 10) it will behave like a push at Y (above the horizontal) and will take out tilt as well as turning the gyro back to the meridian, Fig. 9 (b).

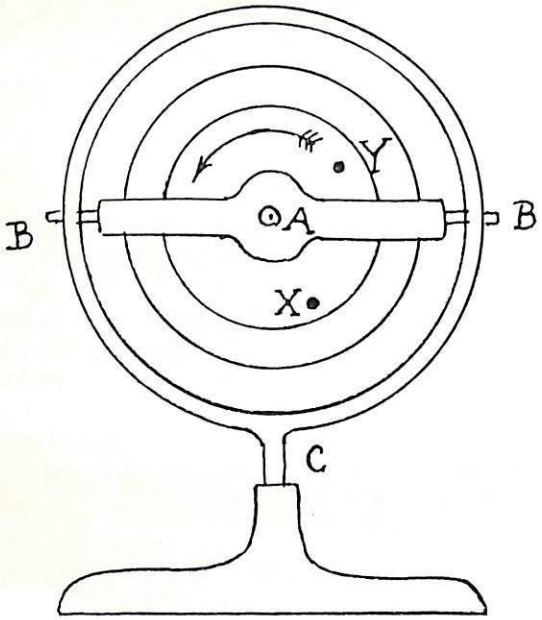


FIG. 10.

To achieve this the bail must not be mounted on the spinning wheel but on some separate member.

9. Settling point.—It will now be apparent that it is tilt effect which makes the compass North seeking, and at any place other than the Equator the compass must be turning at the same rate as the drift if it is to keep on the meridian.

In the N. hemisphere the compass we have been discussing will settle with its N. end East of the meridian and pointed up at A in Fig. 9 (b). The bail will be pressing into the paper at X in Fig. 10. This push in at X will act like a push in at Y which is a two-fold effect.

1. A movement anti-clockwise around the vertical axis just sufficient to equal the drift for that latitude and so enable the compass to remain on the meridian, and :—

2. A movement on the horizontal axis tending to put the N. end down but just sufficient to balance the tilt effect trying to left the N. end up.

In the S. hemisphere the settling point will be with N. end to the West of the meridian and down at B in Fig. 9 (b). This will give a precession of N. end to the East equal to the drift of the meridian and a tendency for the N. end to lift equal to the tilting effect.

10. Auxiliary Latitude Correction.—The compass then will not settle horizontally on North but will have a settling point (both as regards heading and tilt) which will depend on the latitude. The correction necessary to rectify this is the auxiliary latitude correction.

11. Latitude Speed Error.—It is the rotation of the Earth to the Eastwards which gives the compass its North seeking property. The compass tries to set its axle at right angles to its movement in space. If the ship is steaming North, and at the same time the Earth is turning East the movement of the compass in space is N.-E'ly (Fig. 11).

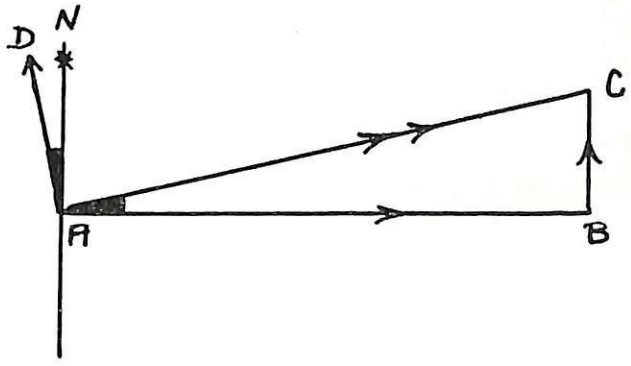


FIG. 11.

AB represents the movement of the place towards the East in an hour, this is 15° or 900′ of d.long. or 900 × cosine latitude nautical miles per hour (ask any Second Mate !). BC is the distance the ship makes N. in an hour and is therefore equal to ship's speed × cosine of the course. The

movement of the gyro in space is therefore AC and it will set its axis at right angles to AC that is along AD and will therefore produce a W'ly error of $\angle NAD = \angle CAB$. Now, obviously tan $\angle CAB = \frac{CB}{AB}$

$$= \frac{\text{Speed} \times \text{cosine course}}{900 \cos \text{latitude}}.$$

It is more usual to say :—

$$\text{Sine error} = \frac{\text{Speed} \times \text{cosine course}}{900 \cos \text{latitude}}$$

but sine and tangent of small angles are the same, and in any case ABC is not a plane triangle.

$$\text{On error in radians} = \frac{\text{Speed} \times \text{cosine course}}{900 \cos \text{latitude}} \times \frac{180}{\pi} = \frac{\text{Speed} \times \text{cosine course}}{5\pi}.$$

This error—W'ly on N. courses and E'ly on S. courses is variously called the "latitude-speed error," the "speed-course error" and the "North steaming error."

12. Repeaters.—Having got our compass, if we want to work repeaters from it we must do so without interfering with the freedom of the spinning wheel. We must, if possible, follow the movements of the spinning wheel without touching it.

EXERCISE I.

Do these exercises as you come to them they will test if what you have read has sunk in.

1. If a cyclist is falling over to port which way must the handle bars be turned to straighten him ?

2. What are the two main gyroscopic laws ? Why will a gyroscopic top balance on a string ?

3. What is meant by "three degrees of freedom" ?

4. In latitude 50° N. a gyroscope is started in the following positions, in which direction would you expect it to start to move ?

   (*a*) N. end pointing N. and horizontal.
   (*b*) N. end vertically up.
   (*c*) N. end East and horizontal.
   (*d*) N. end West and 45° up.

5. If the end of the axis of a gyroscope wheel, which is spinning clockwise, is pushed to the left, how will it move ?

6. What is the effect of making a gyroscope pendulous ?

7. What is meant by a "damped" curve ?

8. How does a gyro compass settle (*a*) in N. hemisphere (*b*) in S. hemisphere.

9. Why is an auxiliary latitude correction necessary with a gyro compass ?

10. What is latitude-speed error ? Steaming S.W. 20 knots in S. latitude, what will be the name of this error ?

11. If N. end of rotor oil well contains more oil than the S. end, thus causing a pressure down on the N. end, what error will this cause ?

12. A ship's compass has N. end of spin axle deflected 30° to E. of the meridian. Explain briefly the cycle of the N. end of spin axis before settling point is reached.

13. How would a slight clockwise twist on the vertical axis of a free gyro affect the heading of the gyro ?

14. Explain the relation between speed error and rate of change of latitude.

15. How does tilt vary with latitude and azimuth ? What is the rate of tilt in a gyro spinning with axis pointing 30° T in latitude 52° N. ?

16. What is the angular rate of drift of a gyro in latitude 52° N.

CHAPTER II.

THE SPERRY COMPASS

13. Spinning the wheel.—So far it has all been theory. The question now is how to do the thing in practice. The first job is to spin the wheel. It must spin fast, therefore it must be of simple robust construction, for powerful centrifugal forces would soon tear apart a flimsy structure with thin wire windings. If possible the bit that goes round should not have electrical connections to it or this would necessitate slip rings, and that would mean friction and make it harder to turn. The answer is a three phase A.C. induction motor. (See " Munro's Electricity and Magnetic Compass," § 989.)

The Sperry compass uses 3-phase A.C. 210 cycles at 50 v. This is produced by a generator driven by a D.C. motor. The motor is operated by 70 v. D.C. current obtained from the ship's 110 v. or 220 v. supply.

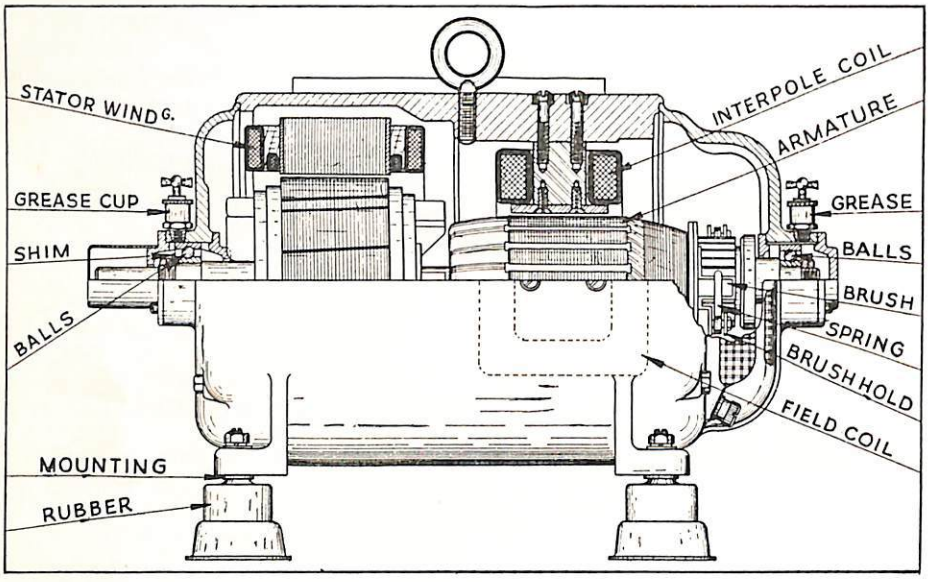


FIG. 12.

The three phase current is carried by three wires to windings inside the rotor case. The rotor itself is the squirrel cage armature of the induction motor and is arranged to rotate at about 6000 r.p.m., it weighs about 50 lbs.

13a. Speed of the wheel.—The face of the wheel is marked with a black spiral which shows through a window (Fig. 14). When the wheel is turning the correct way (that is anti-clockwise looking at the S. end) the spiral will appear to move out over. Interchanging any two of the three phase leads will cause the wheel to rotate in the opposite direction.

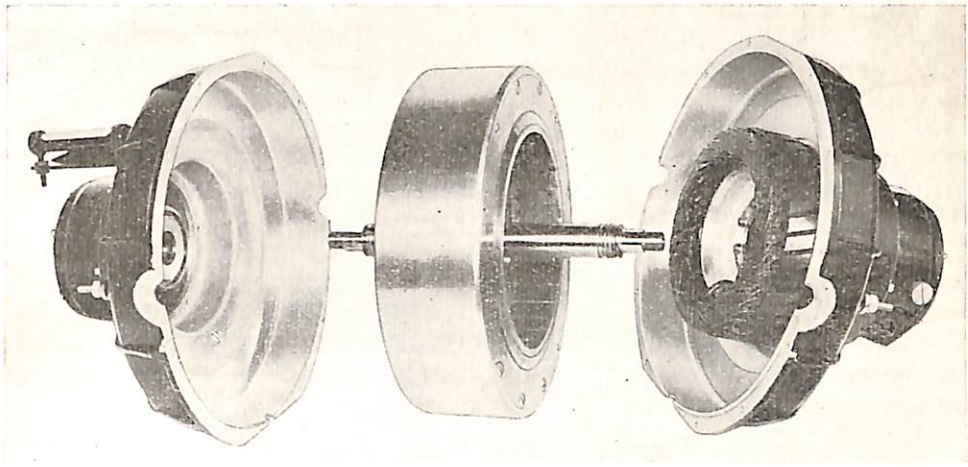


FIG. 13.

The speed of the wheel is dependent upon the speed of the generator, and therefore on the supply current.

The speed of the wheel can be measured by a stroboscope (Fig. 14) not usually possessed by a ship.

The stroboscope carries a disc pierced with ten holes. The disc can be rotated by a handle and its speed is indicated on the dial. The observer stands in a convenient position so that the rotor window can be seen through the holes in the disc. If the disc is turning at one tenth of the

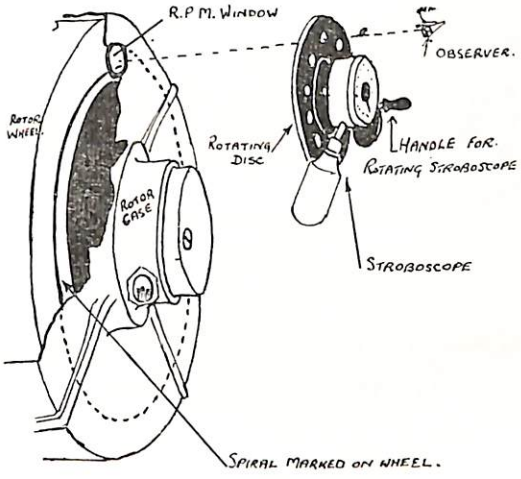


FIG. 14.

speed of the rotor then by the time the disc has turned from one hole to the next the rotor will have made one complete turn. It will thus be seen that every time the observer sees the wheel through the disc, he will see the same part of the spiral, and the spiral line will appear to stand still. Ten times the speed of the stroboscope will be the speed of the rotor.

14. First degree of freedom.—The first degree of freedom is on the spinning axis (Fig. 13). A 50 lb. wheel rotating at nearly 6000 r.p.m. will require satisfactory lubrication. The end of the spinning axle runs in a ball race which is oiled by three wicks which dip down into an oil reservoir contained in the hub of the rotor case. The oil reservoir can be filled or emptied through the oil plug by using a syringe. A window is fitted to the oil reservoir and the correct oil level is half way up the window (22, Fig. 15).

The rotor case will fall over if the wheel is not running, and if it lay on its side the oil may find its way into the rotor windings. A clip is fitted to the vertical ring so as to hold the spinning axle horizontal (31, Fig. 18). The spinning axle is also cut with a thread (an archimedean screw) which throws oil outwards when the wheel is running and so prevents leakage into the windings (Fig. 13).

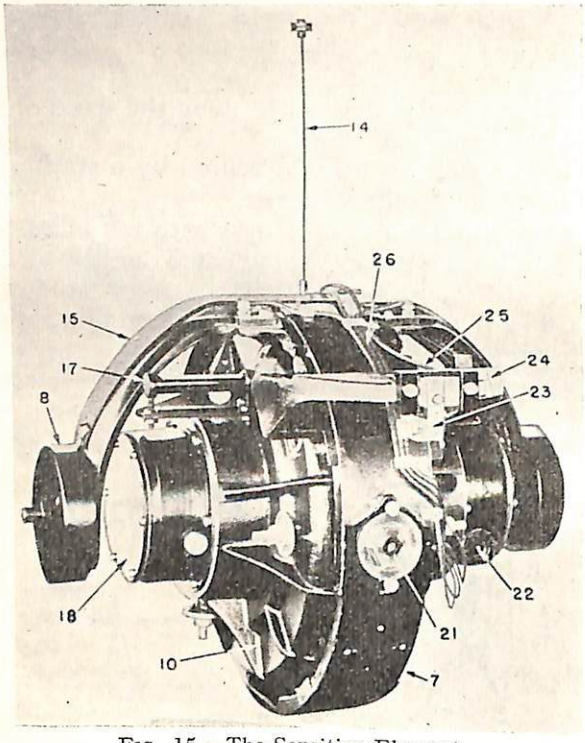


FIG. 15.—The Sensitive Element.

7. Vertical Ring.
8. Compensator Weight.
10. Rotor Case.
14. Suspension.
15. Compensator Weight Frame.
17. Case Level.
18. Rotor Bearing Housing Plate.
21. Horizontal Case Bearing.
22. Oil Well Window.
23. Trolley.
24. Trolley Bracket.
25. D.C. Return from Trolley.
26. A.C. 3 Phase Supply to Gyro.

15. Second degree of freedom.—The rotor case is pivoted inside the vertical ring by the East and West bearings. These are ball bearings (21).

The rotor and its case with the vertical ring and compensator weighs are called the "sensitive element."

16. Third degree of freedom.—Since the gyro is to be used as a compass then freedom about the vertical axis is of paramount importance. The sensitive element is suspended by a stranded steel wire—the strands are straight not laid up. The sensitive element will thus be free to turn through a very small angle, but the resultant twist in the wire will then prevent its turning further. If, however, we can arrange things so that the top end of the wire turns as soon as the bottom end turns then the twist will be kept out of the wire. To understand how this is achieved we must consider the design of the binnacle.

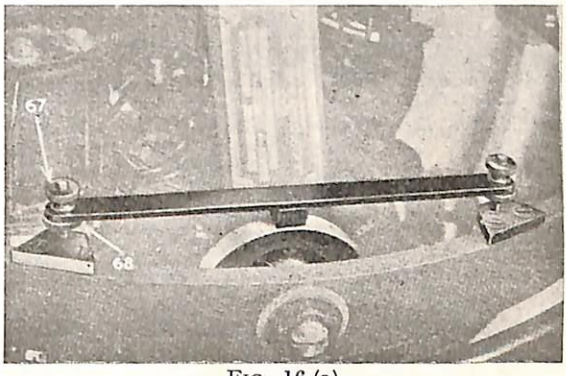


FIG. 16 (a).
67. Clamp Nuts. 68. Adjusting Nuts.

The binnacle is secured to the deck. At the top of the binnacle are two gimbal rings. One of these is pivoted athwartships, for pitching movement. This is fitted with a friction brake, the normal setting for which is just to grip a piece of writing paper, Fig. 16 (a).

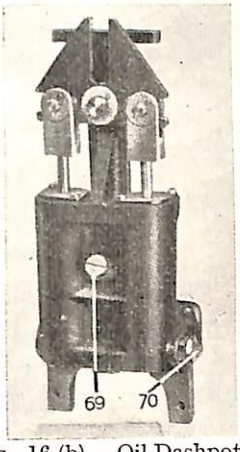


FIG. 16 (b).—Oil Dashpots.
69. Oil Filler Screw. 70. Regulating Valve.

If the ship is pitching heavily this friction brake should be tightened up. Reset when weather moderates.

The second gimbal ring is pivoted fore and aft for rolling movements and is fitted with dash pots to restrict the movement, Fig. 16 (b).

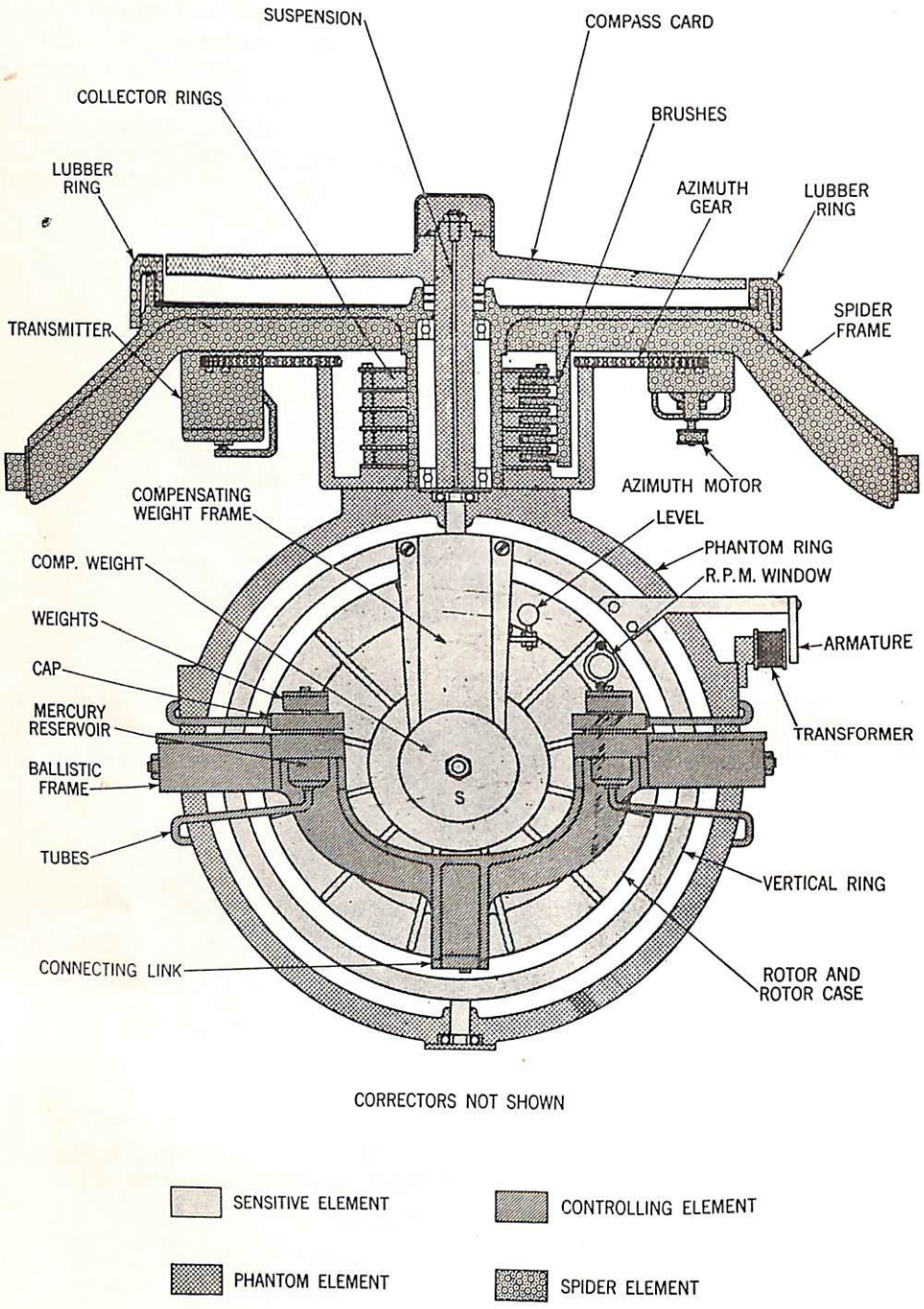


FIG. 17.—Four Elements of the Gyro Compass.

Attached to the gimbal rings is a bridge-like framework, the spider frame (Fig. 17) which supports the whole gyro compass. This framework is now in the form of a cross (see Fig. 25), but originally it had six legs, and hence its rather strange name.

The compass card rests on top of the spider element and is firmly attached to the upper end of the suspension wire.

The suspension wire attaches at its lower end to the vertical ring inside which is pivoted the rotor and case by means of the East-West bearings.

Fastened to the compass card, and extending below the spider is the upper stem assembly. This carries a big gear wheel (the azimuth wheel) which meshes into the gearing of an electric motor (the azimuth motor) which is fixed to the spider element.

Fixed to the lower end of the upper stem assembly is the phantom ring which encircles the vertical ring.

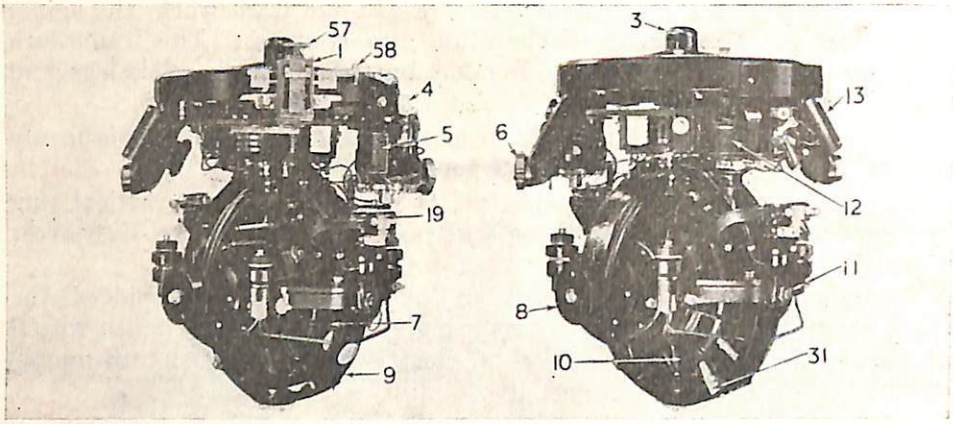
If the phantom ring (attached to the upper end of the wire) is in line with the vertical ring (attached to the lower end) there is no twist in the wire. As soon as the " ship " moves (bringing the phantom ring out of line with the vertical ring) the azimuth motor is started up, ahead or astern, so as to turn the phantom (and the card) back into line with the vertical ring. There are two methods of effecting this, viz. :—the trolley contactor system or the valve follow-up system (V.F.U.).

17. Trolley contactors.—In this system the azimuth motor is switched on and off by a simple mechanical arrangement. Although this type is not now in production many such sets are still in use. A trolley bracket is fitted to the vertical ring and this carries a trolley wheel which runs on contactor blocks on the phantom ring (Fig. 18). The contactor block is in two halves separated by a small air gap. If phantom and vertical rings are exactly in line the trolley wheel will be on the air gap between the two blocks. If the sensitive element moves slightly it will bring the trolley wheel onto one of the contact blocks. This completes a circuit and energises the azimuth motor. When the azimuth motor turns, it turns the gear wheel and so turns the phantom ring until the gap is once again under the trolley wheel.

In actual fact the phantom gathers momentum and overshoots the little gap, bringing the trolley onto the other contact block, which reverses the azimuth motor. In this way the trolley does not come to rest but " hunts " backwards and forwards across the gap.

The azimuth motor is a D.C. motor with separately energised field. The armature current flows the opposite way when the trolley is on the other block. With the trolley on one block the motor will run ahead, and with the trolley on the other block it will run astern, or a split field motor can be used.

Now this arrangement really interferes with the freedom of the sensitive element and so the pressure on the trolley must be very light. A certain amount of sparking will take place and the trolleys require frequent cleaning. Care must be taken in cleaning trolleys not to make a flat on the trolley wheel.



South View. North View.

FIG. 18.—The MK. XIV. Gyro Compass.
(Removed from the Binnacle).

1. Speed and Latitude Corrector.
3. Suspension Cap.
4. Transmitter Lost Motion Adjusting [Knob.
5. Transmitter.
6. Trunnion Bearings.
7. Vertical Ring.
8. Compensator Weight.
9. Phantom Ring.
10. Rotor Case.
11. Mercury Ballistic.
12. Azimuth Motor.
13. Spider Terminal Block.
19. Trolley Adjusting Screw.
31. Vertical Ring and Rotor Case Lock.
57. Speed and Latitude Corrector Setting Knob.
58. Auxiliary Latitude Corrector Setting.

There are two sets of trolley wheels and contact blocks, one on each side of the compass. This doubles the switching arrangement in case contact is not made by one trolley. One set can also be moved slightly. The effect of this is shown in Fig. 19 where, for simplicity, both trolleys are shown on the same pair of contact blocks. If the trolleys are close together as in 19 (a) there will be some " slack " in the arrangement and the compass will have a big-slow hunt. If the wheels are wide apart, as in 19 (b) there is no slack and the compass will have a small hunt. The system should be adjusted to give a hunt of $\frac{1}{2}°$.

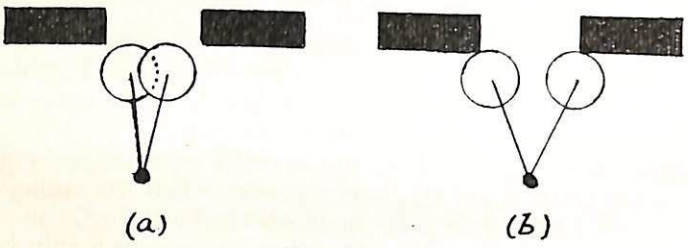


FIG. 19.

The system has two faults (although it works well). One fault is that it interferes slightly with the freedom of the sensitive element, and the other is that the trolleys require frequent cleaning although they are very readily removable for this purpose.

18. Valve follow up.—In the valve follow up system the switching of the azimuth motor is achieved by electronic means. If an A.C. current flows through the primary winding of a transformer it will produce an A.C. current in the secondary winding. This induction effect is caused through magnetic changes, and to enable the transformer to work efficiently the two coils are usually wound on a soft iron former. (See "Munro's Electricity and the Magnetic Compass," § 58).

There is an E transformer fixed to the phantom ring of the gyro compass and a soft iron plate (C in Fig. 20) is fixed by a bracket to the vertical ring.

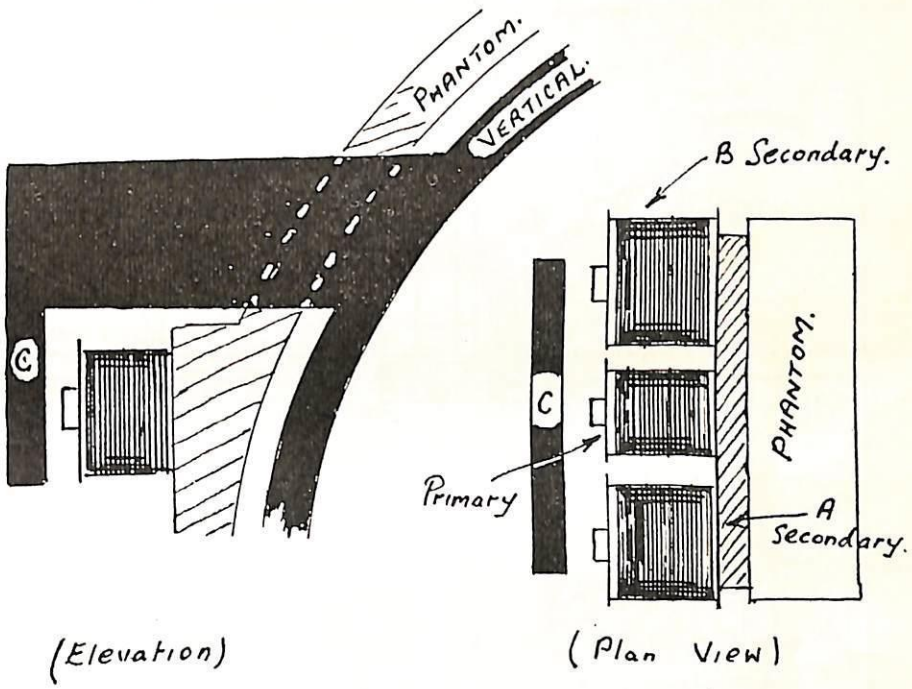


FIG. 20.

The E transformer consists of three coils wound on an E-shaped former. The centre coil is the primary and the two outside coils are secondaries. We will call the right hand one A and the other B. The currents induced in the secondaries will be out of phase because the windings are in opposite directions. For an explanation of phase see Chapter VI.

Now if the phantom and vertical rings are exactly in line the soft iron plate (C) will be exactly in the middle and the output of the two secondaries will be equal, and since they are 180° out of phase they will cancel each other, Fig. 21 (a). If the ship moves a little way it will bring the iron plate more on one side than the other. In Fig. 20 imagine the ship and phantom ring with its coils to swing and so bring the plate more over B coil than A. The output from B will be greater than the output from A and the result will be a signal having the same phase as B, Fig. 21 (b). This small signal current can be used to start the azimuth motor which

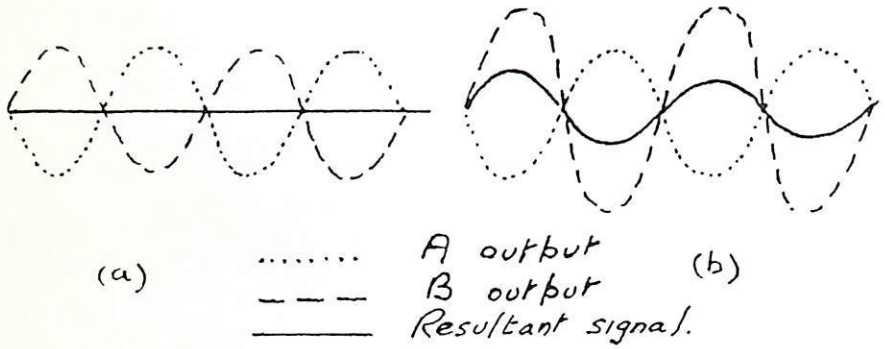

(a)
A output
B output
Resultant signal.
(b)

FIG. 21.

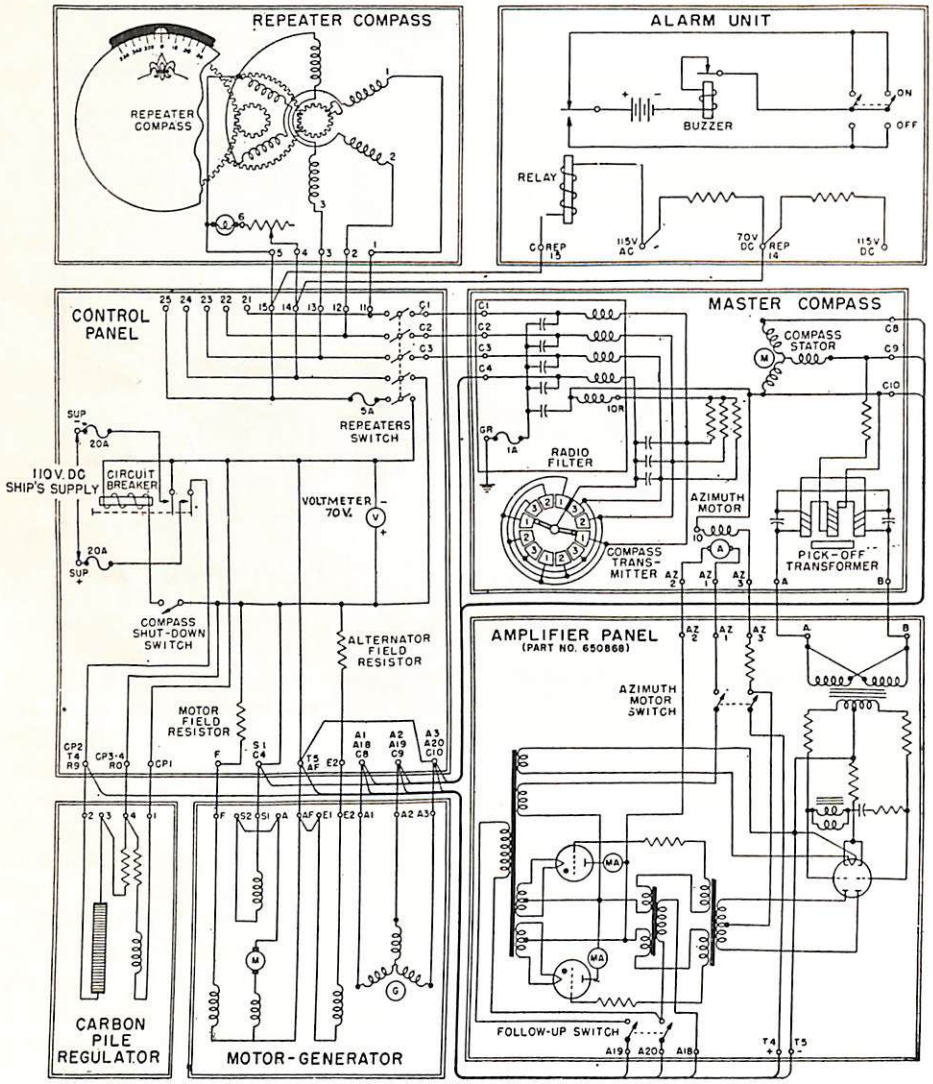

REPEATER COMPASS
REPEATER COMPASS
ALARM UNIT
BUZZER
ON
OFF
RELAY
CONTROL PANEL
REPEATERS SWITCH
110V. DC SHIP'S SUPPLY
CIRCUIT BREAKER
VOLTMETER 70V.
COMPASS SHUT-DOWN SWITCH
ALTERNATOR FIELD RESISTOR
MOTOR FIELD RESISTOR
MASTER COMPASS
COMPASS STATOR
RADIO FILTER
AZIMUTH MOTOR
COMPASS TRANS-MITTER
PICK-OFF TRANSFORMER
AMPLIFIER PANEL
(PART NO. 650868)
AZIMUTH MOTOR SWITCH
FOLLOW-UP SWITCH
CARBON PILE REGULATOR
MOTOR-GENERATOR

FIG. 22.

will drive the phantom to the left until it is again in line with the vertical ring. Before the signal current can be used to operate the azimuth motor, however, several things are necessary. We must amplify it, for it is too weak, and rectify it, for the azimuth motor is a D.C. motor, and we must direct it to the armature so as to run the motor ahead or astern as required.

19. The amplifier.—The signal current is fed to the amplifier (Fig. 22).

The amplifier contains three valves. The centre one is a pentode amplifying valve and the other two are gas-filled triodes which operate as trigger valves to start the azimuth motor running ahead or astern according to whether the signal has the phase of A coil or of B coil.

Chapter VII. gives a layman's explanation of valve operation.

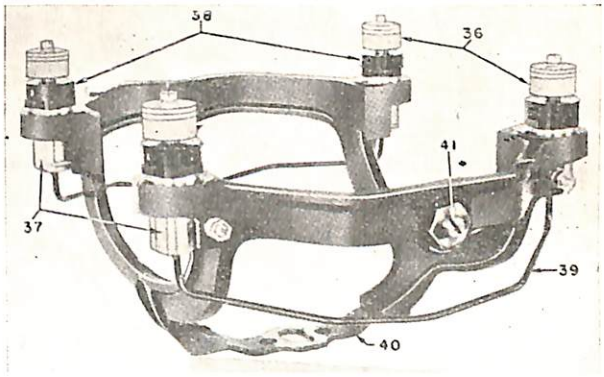


FIG. 23.—The Control Element.
(Mercury Ballistic).

36. Balancing Weights.
37. Mercury Reservoirs.
38. Mercury Reservoir Covers.
39. Mercury Tube.
40. Link Arm.
41. Ballistic Bearing Stud.

20. The mercury ballistic.—Instead of using a solid weight, or bail, to produce the N.-seeking property the Sperry gyro uses a mercury ballistic (Fig. 23).

The framework pivots on the phantom ring and carries four bottles—part filled with mercury. Each N. bottle is connected to its corresponding S. bottle by a thin pipe so that if the frame is tilted on its pivots mercury can run from N. to S. or *vice versa*. On the bottom of the rotor case is the eccentric pivot displaced about $\frac{3}{16}''$ to the East of vertical. A link arm passes between the rotor case and vertical ring, resting on the eccentric pivot in the middle, and being fixed to the framework of the mercury ballistic at both ends. By this means damping is achieved as explained in § 8.

If the gyro is started pointing North and horizontal, the turntable effect swings the N. end East. Tilt effect now lifts the N. end up. Mercury flows into the S. bottle. The weight of the mercury pushes the link against the eccentric pivot. Because of the law of precession this push

acts on the East side and a little above middle (near the window). It therefore turns the compass back towards the meridian and levels out the tilt.

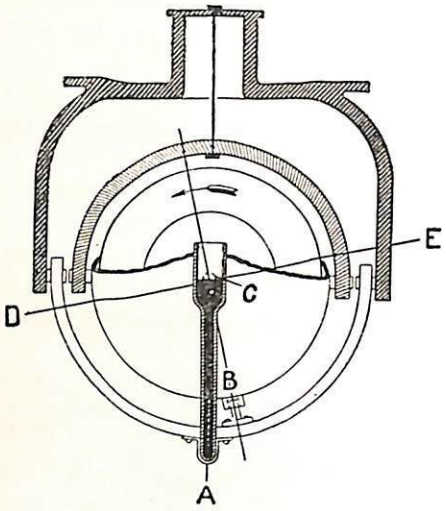


FIG. 24.—Mercury Ballistic attached to the Gyro-wheel casing eccentrically.

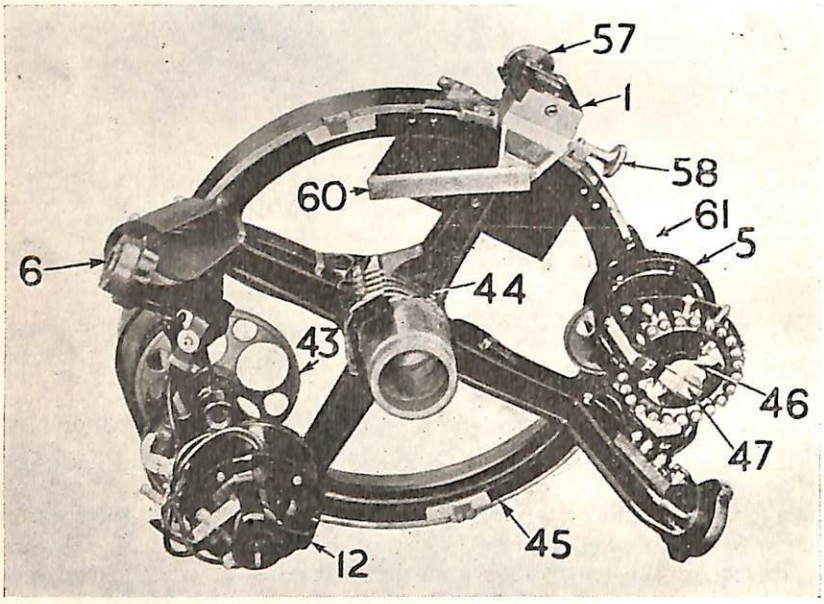


FIG. 25.—The Spider Element.

1. Speed and Latitude Corrector.
5. Transmitter.
6. Trunnion Bearings.
12. Azimuth Motor.
43. Azimuth Motor Large Gear.
44. Stem Collector Ring Brushes.
45. Lubber Ring.
46. Trans. Roller Carriage.
47. Trans. Centre Contact Arm.
57. Speed and Lat. Corrector Setting Knob.
58. Aux. Lat. Corrector Setting Knob.
60. Cosine Cam Arm.
61. Knob for adjusting lost motion.

21. The auxiliary latitude corrector.—On the after-end of the compass there is a knob which is attached to a block marked with latitude from 70° N. to 70° S. As the knob is turned and the observer's latitude is set, the lubber ring is moved the amount necessary to correct the auxiliary latitude error (See § 9).

22. Latitude speed corrector.—Also on the after-end is a knob which drives a scale marked in latitude across a set of speed curves (Fig. 26) and this sets the latitude speed correction. It will be remembered that the latitude speed correction also involves the cosine of the course but that part of the correction is performed automatically.

The arm (60) is fitted with a pin and a brass bush (59) which runs in a deep groove (the cosine groove) which is cut in the under side of the big azimuth gear wheel. The cosine groove is eccentric to the gear wheel so that as the course is changed the arm (60) is swung in and out. The

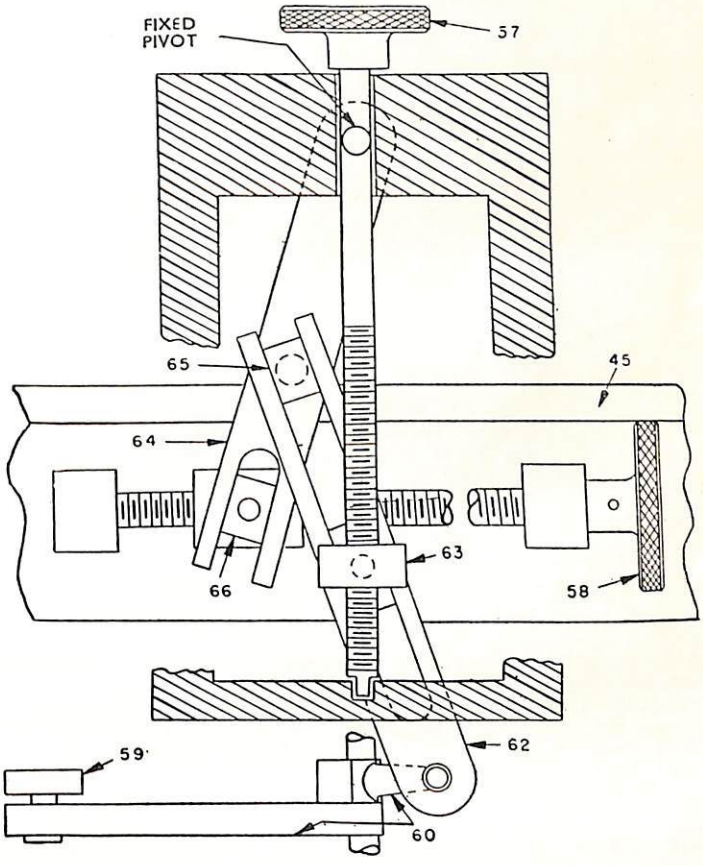


FIG. 26.—Speed and Latitude Corrector Mechanism.

45. Lubber Ring.
57. Speed and Latitude Setting Knob.
58. Aux. Latitude Setting Knob.
59. Cosine Cam Roller.
60. Cosine Cam Arm (Bell Crank).
62. Arm.
63. Adjustable Pivot.
64. Arm.
65. Fixed Pivot.
66. Adjustment Block and Pivot.

movement of the arm, operating through a system of levers, moves the lubber ring sufficiently to correct the latitude speed error. As the speed setting is reduced by turning the knob, the two pivots (63) and (66) are brought together until with speed setting " nil " they are brought in line. There is then no leverage from one to the other and consequently no movement of the lubber line. When a high speed and latitude are set, however, (63) and (66) are moved apart and the consequent big leverage makes any movement of the arm (60) cause a proportionately large movement of the lubber line.

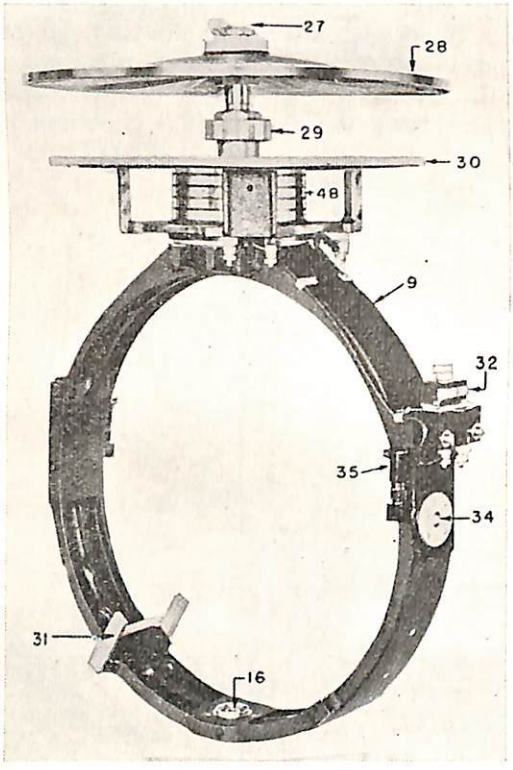


FIG. 27.—The Phantom Element.

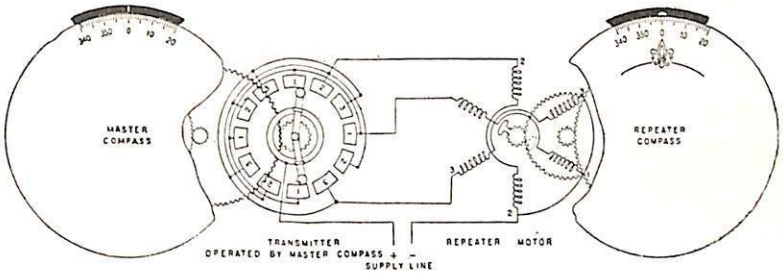
9. Phantom Ring.
16. Lower Guide Bearing.
27. Suspension Adj. Fork.
28. Compass Card.
29. Upper Stem Bearing.
30. Azimuth Gear.
31. Vertical Ring and Rotor Case Lock.
32. Contactor.
34. Mercury Ballistic Bearing.
35. Mercury Ballistic Bearing Oil Cup.
48. Stem Slip Rings.

23. The transmitter.—Fixed to the lubber ring opposite to the azimuth motor is the transmitter which operates the repeaters. It consists of a distributor arm moving around a number of copper segments (No. 46, Fig. 25).

If the master compass turns $\frac{1}{3}°$ it moves the distributor from one segment to the next. The segments are connected to the coils of a step-by-step motor in the repeater which turns the same amount as the compass

card. (See " Munro's Electricity and the Magnetic Compass," § 65.) A caging knob on the side of the repeater enables it to be synchronised with the master. The transmitter works in half steps of 10 minutes.

The spindle of the transmitter incorporates a lost motion device illustrated in Fig. 29.



Schematic Diagram showing how the Repeater Compasses are operated from the Master Gyro compass

FIG. 28.

The triangular piece of metal B can be raised or lowered by turning the knob A. If screwed right down it presses against the arms CC and the least movement of the master card is transmitted to the distributor arm. If, however, B is screwed up it will only turn C when the compass has moved an appreciable amount, and this enables small movements to be lost making the repeaters dead beat (*i.e.* not hunting). Even with V.F.U. system the master compass will hunt, but in this case the hunt is only about $\frac{1}{10}°$.

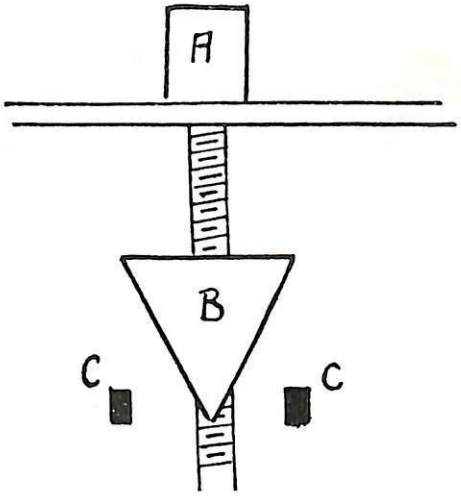


FIG. 29.

24. Electrical arrangement (See Fig. 22).—The compass is supplied from the ship's D.C. supply (usually 110 v.) this is reduced to 70 v. by series resistors. The supply is smoothed out to a steady 70 v. by a carbon pile regulator (" Electricity and the Magnetic Compass," § 66). A D.C. meter on the control panel indicates the voltage after smoothing, and this should always read 70 v.

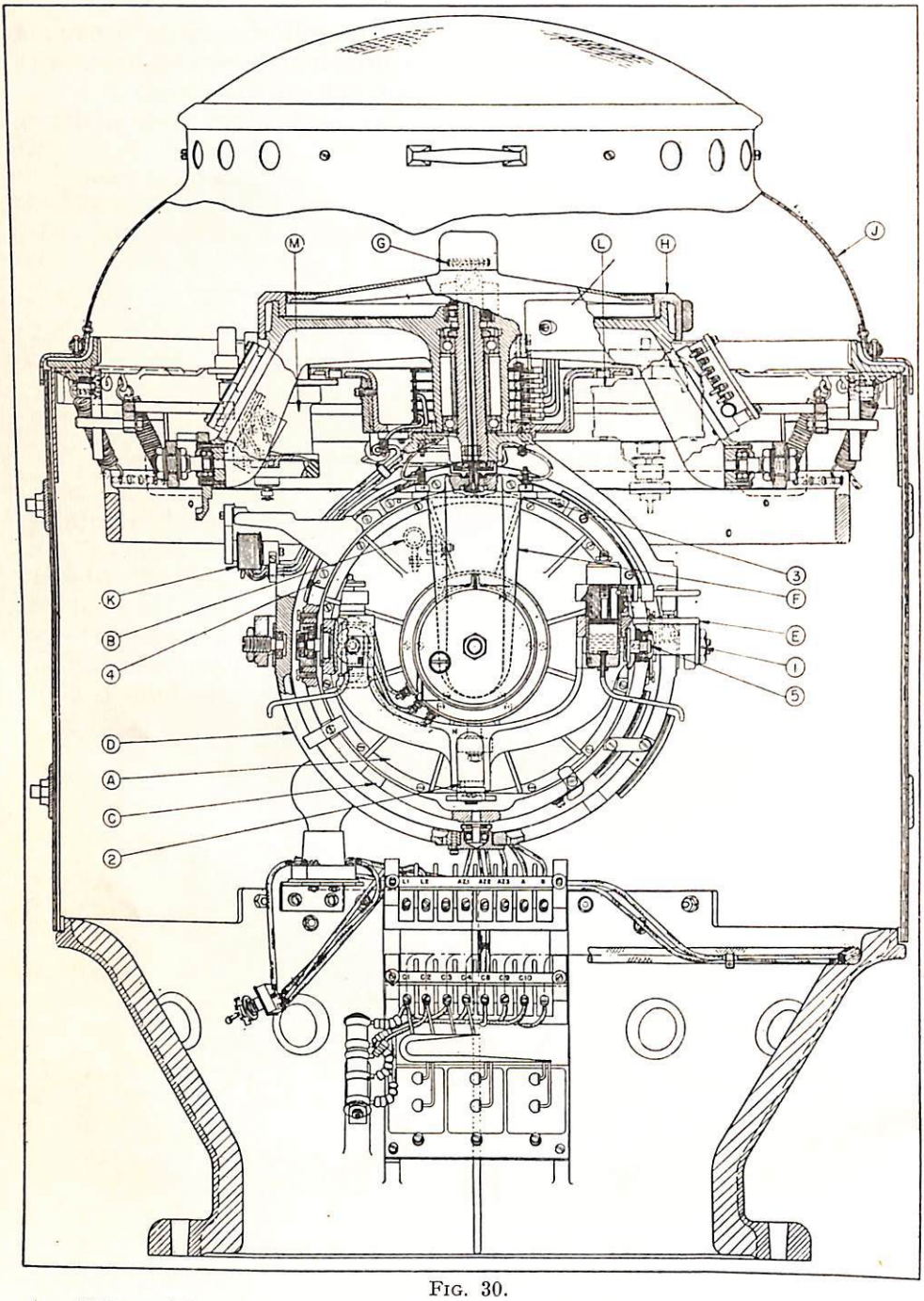


FIG. 30.

A. Rotor and Case Assembly.
B. Level Assembly (with Bkt.
C. Ring Assembly, Vertical.
D. Element Assembly, Phantom.
E. Ballistic Assembly, Mercury.
F. Compensator Weights and Frame Assembly.
G. Corrector Assembly.
H. Member Assembly, Outer.
J. Binnacle Assembly.
K. Follow-Up Device Assembly, Electro Magnetic.
L. Motor Assembly, Azimuth.
M. Transmitter Assembly.

The ammeter on the amplifier panel shows the plate current in the triodes and should read 0·3 A with a slight flutter.

An alarm bell is incorporated to serve as a power failure warning. The circuit is shown in Fig. 22. The alarm is operated by dry cells. If the bell rings it means that the power has failed and if the failure lasts for more than a minute or so the circuit breaker will fall out and the compass will have to be restarted. The circuit breaker is a no-volt release for the motor generator. (" Electricity and the magnetic Compass," § 77.)

The 3-phase current for spinning the wheel is produced by the motor generator and enters the binnacle at the bottom. It is then led up via the main terminal block to the spider element. A sliding connection is necessary to enable the compass to turn freely and this is provided in the upper stem assembly where metal fingers run on metal rings. Since this part of the equipment is turned by the azimuth motor, not by the sensitive element, friction is permissible.

The three wires then are led down the vertical ring to a point near the horizontal bearing (see Fig. 15), where they step across to the rotor case as three flexible braided leads. These leads should be standing out in bights, not touching the rotor case since their weight may cause some precession.

24a. The consequences of some mal-adjustments.

(*a*) Effect of a twist in the suspension.—If the twist is not excessive a clockwise twist, as viewed from above, will cause the N. end to tilt up and mercury will flow to the South end. The compass will settle West of its normal position so that the earth's tilt effect tending to depress the N. end will balance the tendency of the N. end to lift because of the twist in the suspension.

(*b*) Effect of an added weight say on the N. side of casing.—The weight will cause the N. end to precess to East, when earth's tilt effect will tilt the N. end up. Mercury will flow to South bottle. The settling position is to the East and tilted up, in such a position that the excess mercury in the S. bottle is the same weight as the added weight.

(*c*) Effect of a weight added to N. side of the mercury bottles.—This will cause a wander in an anti-clockwise direction, the compass finally settling with N. end tilted up but on the usual heading.

(*d*) An alteration in rotor speed.—If the speed is increased a larger torque will be necessary to produce a precession equal to the drift of the meridian (§ 3) and in the Northern hemisphere the compass will settle on the same heading as before but with a bigger tilt. With varying voltage the compass will be continually trying to reach new settling points and will wander.

(*e*) If the lower guide bearing is dirty it will cause a restriction on the vertical axis, and the effect will be the same as (*a*) above but of variable value.

EXERCISE II.

1. Explain how freedom about the vertical axis is achieved in a Sperry gyro compass.

2. Describe the advantages of the V.F.U. system as against the trolley contractor.

3. What is the " spider element " ?

4. What is the " phantom ring " ? How is it made to haunt the vertical ring ?

5. What arrangements are there to prevent excessive movement when pitching and rolling ?

6. Describe fully the operation of a repeater compass.

7. What is the eccentric pivot, and why is it eccentric ?

8. Describe the mercury ballistic.

9. What is the cosine groove ?

10. Why is an auxiliary latitude correction necessary ? How is it affected ?

11. Why do repeaters not hunt ?

12. How fast does the wheel of a Sperry gyro rotate ? How is it oiled ?

13. There are two catches on the Sperry gyro compass. What are they for ?

14. What is indicated if the alarm bell of a Sperry compass rings ?

15. What adjustments are necessary if the ship changes her latitude ?

16. How do you know if the rotor is turning the correct way ?

17. If the pentode valve failed what do you think would happen ?

18. Explain how a carbon pile regulator works.

19. Sketch and describe a step-by-step motor.

20. What is the normal value of hunt (*a*) with trolley contactors, (*b*) with V.F.U. ?

CHAPTER III.

MORE THEORY.

25. Ballistic turn effect.—Let us imagine a ship steaming N. As we have seen latitude speed error will be W'ly, but the corrector will move the lubber line to the West by the necessary amount. Now suppose the ship turns to an East course, as she turns, the latitude speed corrector arm running in the cosine groove will cause the lubber line to move back. It will, however, take some time for the gyro axle to turn back to the meridian, for it was, of course, to the West of the meridian when the ship was steaming North. If this were the whole story there would be a small error on changing course—but this small error would slowly disappear. Fortunately this is not the whole of the story because, as the ship was steaming North, the pipes on the mercury bottles would be fore and aft. When the ship turns off East the mercury in the bottles will try to continue its movement to the North. Some mercury will be transferred from the South bottle to the North bottle. This mercury will cause the N. end of the gyro to move to the East, and this is in the direction in which we want it to move. Now, if only we can arrange for the correct amount of mercury to be transferred, this so called ballistic effect will just cancel the change in latitude-speed error.

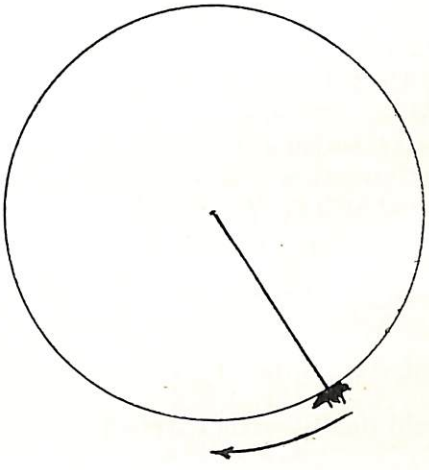


FIG. 31 (a).

This can best be achieved by making the periodic time of the compass about 84 mins. The period of swing of a pendulum is controlled by its length and 84 mins. is the period for a pendulum whose length is equal to the radius of the Earth. Without assuming a much better knowledge of mechanics than is justified it is not easy to explain why this is the case.

In Fig. 31 (a) we picture the ship steaming around the meridian as being similar to a pendulum equal in length to the radius of the Earth.

Stopping the ship will bring into play forces which are related to those necessary to stop such a long pendulum. If the period of the compass is also 84 mins. then the forces necessary to move it bear a similar relationship.

The period of the compass, like the period of roll of a ship, depends upon its G.M. and the disposition of the weight and so is settled by the original design.

26. Settling the compass.—If the period of the compass is 84 minutes, that means about $\frac{3}{4}$ hour for half a swing. The damping decrement is $\frac{2}{3}$, which means that if the compass is 30° off the meridian on one half swing, then on the next half swing, it will be 10° off the other way. That is $\frac{2}{3}$rds has been damped out. Suppose we started the compass back to front—*i.e.* 180° of error.

After $\frac{3}{4}$ hour it would have 60° error.

After another $\frac{3}{4}$ hour ($1\frac{1}{2}$ from the start) it would have 20° error.
$2\frac{1}{4}$ hours from the start the error would be about 7°
3 hours from the start the error would be about 2°
$3\frac{3}{4}$ hours from the start the error would be about 1°
$4\frac{1}{2}$ hours from the start the error would be about $\frac{1}{3}$°
5 hours from the start the error would be negligible.

That is it takes 5 hours for the compass to settle down and it should not be relied upon until it has been running that length of time.

If the compass could be started exactly on its settling point it would stay there, but this involves not only compass heading but also tilt, and so is not easy to do. The compass should be started near its settling point at least 5 hours before it is required.

When the compass is settling it will wander slowly from side to side. If the highest reading on swing is A, the next lowest reading B and the next highest on the next swing is C, then :—

1. Period is from time of A to time of C
2. Damping percentage is $100 \times \left(1 - \frac{C - B}{A - B}\right)$ %
3. The calculated settling point is $B° + \frac{(A-B)\ (C-B)}{(A - B) + (C - B)}$

and the compass should finally settle within $\frac{1}{4}$° of this calculated settling point.

27. Elongated pendulum effect.—If an elongated pendulum, shaped like a hammer head, is swung to and fro, it will be found that it attempts to set its axis of greatest inertia (heaviest axis) in the plane of swing, see Fig. 31 (b).

Now most of the weight of the wheel is in the East-West plane and if the ship is rolling it will try to set this axis athwartships. The tendency to swing one way is no greater than the other if ship is heading on the cardinal points, but instability is maximum on the inter-cardinal points.

To avoid this, compensator weights are fitted and the weight is thus equally distributed. These weights are also used in balancing the gyro and should not be interfered with (see Fig. 15). In the Brown compass the weights are usually called Q. (quadrantal) weights.

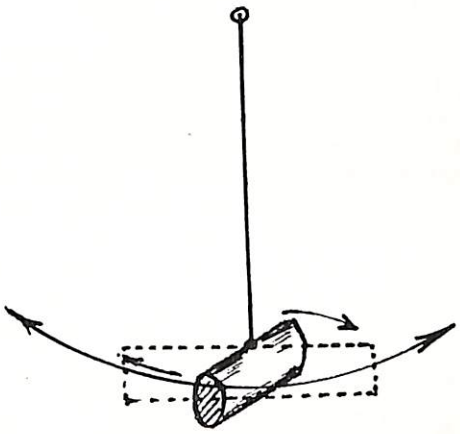


FIG. 31 (b).

28. Rolling error.—In §7 we described how a weight (or bail) would make the gyro compass N.-seeking but the use of a solid weight gave rise to an intercardinal rolling error. If the compass is not situated at the centre of roll it will, when the ship rolls, describe a big arc. At the end of the arc the compass will try to go on whilst the ship comes back.

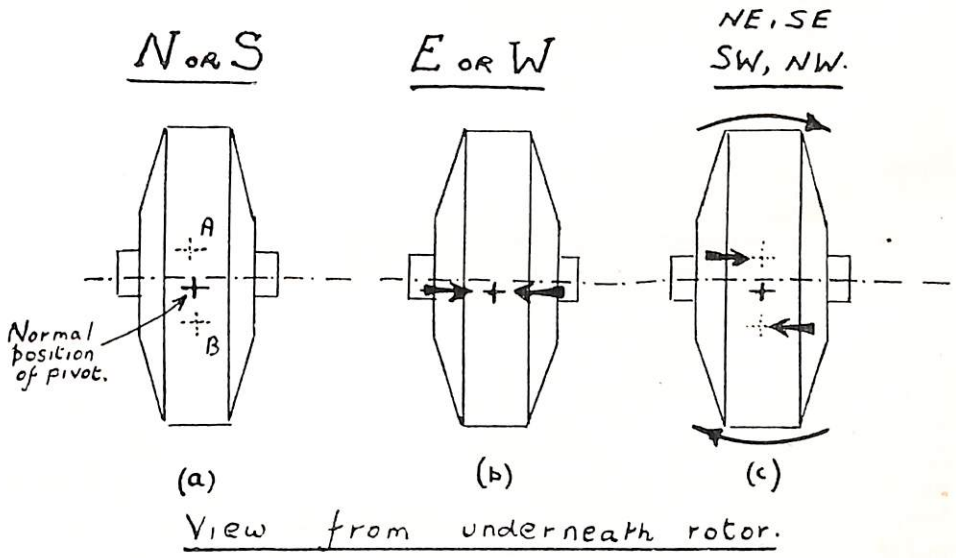


FIG. 32.

If the ship is heading North or South the axis of the wheel and the pipe connecting the bottles will both be fore and aft. At the end of the roll no mercury will be transferred, but the eccentric pivot, which should be a little East of vertical, will be moved back and forth either side of its correct position, Fig. 32 (a). At one half roll it will be at A, and at the next it will be at B. The effects of a steady push on the pivot will cancel out.

When heading East or West the axis and the mercury pipes will be athwartships. At the end of a roll one way mercury will flow into the North bottle, and at the end of the roll the other way mercury will flow into the South bottle. This will put a push, first on one side of the pivot and then on the other side, Fig 32 (b). The period of the compass is long and these pushes will cancel out before they have had time to take effect.

On the cardinal points N., S., E., and W. there will be no error, but on inter-cardinal courses both of these effects will occur together. At one half roll the pivot will move West of normal and get a push on one side, Fig. 32 (c) and at the other half roll it will move East of normal and get a push on the other side. It will be seen from the figure that these effects do not cancel out, but both tend to turn the wheel the same way. The effect is therefore cumulative and very large errors will occur.

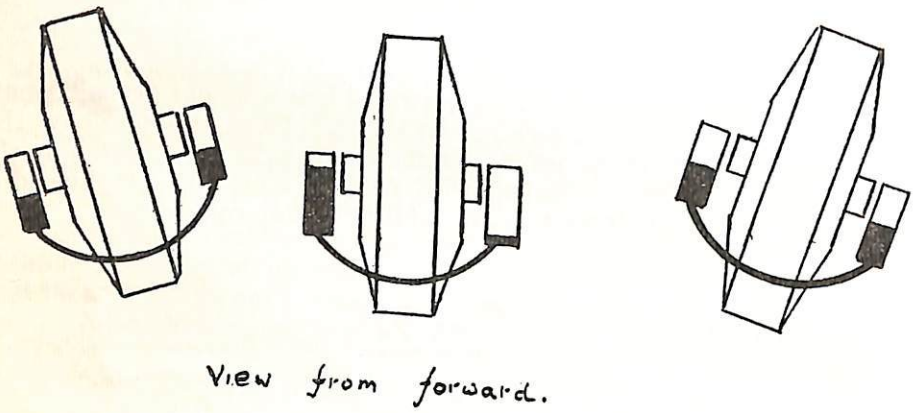


FIG. 33.

By using a liquid ballistic instead of a solid weight the push from excess liquid is delayed until the ship is upright, as we will now attempt to show.

Consider a swinging pendulum : When it is at its extreme position it is momentarily stopped, but when at its mean position it is travelling fastest. This relationship is true of anything moving with harmonic motion. Now consider the movement of the mercury in the bottles. As the ship starts rolling to starboard mercury begins to flow to starboard when the ship reaches the extreme of roll mercury will be flowing to starboard at its fastest. When the ship starts to roll back the mercury will not start to flow back but will continue to flow to starboard as long as this is the low side. It will only start flowing to port after the ship has passed

the upright. Since the movement of the mercury is stopped when the ship is upright, then the mercury reaches its extreme position when the ship is upright and the push is consequently delayed until the eccentric pivot is in its correct position.

In the explanation and figure, the gyro has been shown tilted. Since it is gyroscopically stabilised and is in gimbals, it does not actually tilt, but the acceleration forces which are present have the same effect.

The mercury can only behave in the manner described if the natural period of flow of the mercury is similar to the natural period of roll of the ship. Although the period of roll of a ship varies considerably with different conditions of loading it is nevertheless possible to achieve this agreement.

29. Limitations of the gyro.—From some of the complications briefly discussed it will be apparent that the gyro compass does not indicate true North with supreme accuracy but, if it is in good condition, with all adjustments made, it will not be in error more than about $\frac{1}{2}°$ in good weather and 2° in rough seas.

Since the N.-seeking force is produced by tilt effect, and since tilt effect is nil at the Pole, then the compass will not work at the Pole. Indeed the higher the latitude then the smaller will be the North-seeking force. The compass will, however, be reliable in all navigable latitudes.

Ballistic effects are much greater in aircraft than in ships and consequently N.-seeking gyro compasses of the type discussed here are not a practical proposition for aircraft.

EXERCISE III.

1. Why does a gyro compass require 5 hours to settle down ?

2. What are compensator weights and why are they necessary ?

3. How long does a gyro compass take to make a double swing ? How does this compare with a magnetic compass ?

4. Will a gyro compass work at the geographic Pole ? Will it work at the magnetic Pole ? Why ?

5. Explain why the Sperry compass does not settle with its axis horizontal ?

6. What is meant by a liquid ballistic ?

7. What is ballistic deflection ? What connection is there between the correction of ballistic deflection and speed-latitude error ?

8. What is the purpose of compensator weights, and why are they fitted to the vertical ring ?

9. What is the cosine groove on a Sperry compass ?

10. Why is the period of a gyro compass 84 minutes ?

CHAPTER IV.

THE BROWN GYRO COMPASS

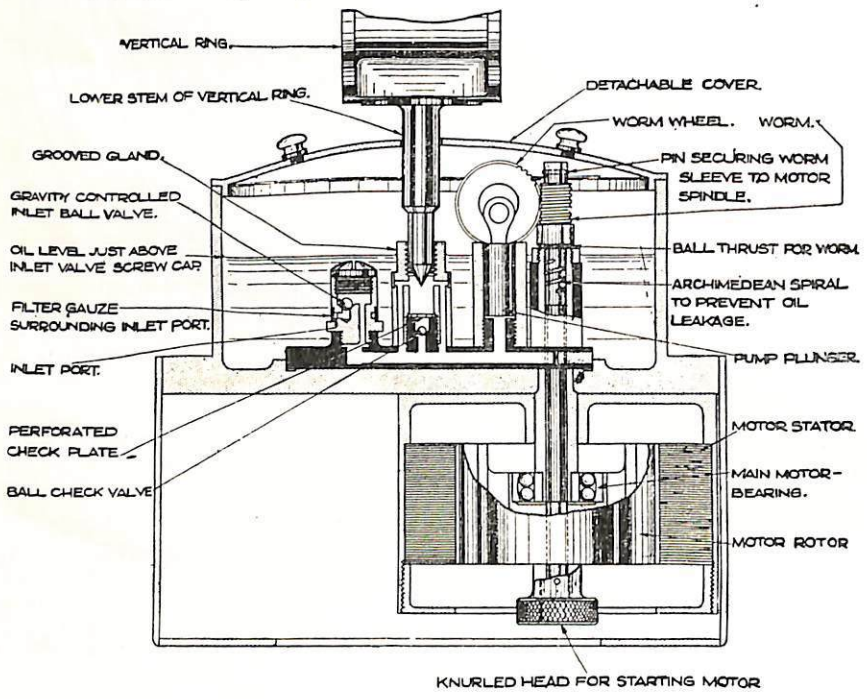
30. The rotor.—The wheel of the Brown compass weighs about $4\frac{1}{2}$ lbs. and rotates about 14,000 r.p.m. It is a three-phase A.C. inductance motor operated by 70 volts at 266 cycles. The wheel is marked with a spiral for use with a stroboscope.

31. The spinning axle is fitted in ball bearings surrounded by a $\frac{1}{4}$" diameter thick cotton wick which is compressed behind a perforated aluminium cage. Any oil seen in the glass window is surplus to this wick being saturated. The normal level of oil is approximately $\frac{1}{4}$ of the distance up the glass window.

32. Second degree of freedom.—The rotor case is pivoted inside the vertical ring on knife edges.

33. Third degree of freedom.—The Brown achieves freedom on the vertical axis in quite a different way from the Sperry. The vertical ring is supported by a stem which dips into an oil well.

The electrically-driven pump drives the plunger down which forces oil along the pipe, closing inlet valve, and opening check valve. This oil pressure lifts the compass until the six side ports are uncovered. As the



Sectional Diagram of Pump

FIG. 34.

plunger rises it sucks oil through the inlet valve, and closes check valve. The compass sinks back again. The compass is thus pumped up and down about $\frac{1}{4}$" a few times a second.

Now there is a principle in mechanics that if we overcome friction between two surfaces in one direction we also overcome friction in a direction at right angles to the first. If, for example, a shaft is greased so that it rotates easily it will also slide in and out easily (if it has no collars). If we wish to extract a cork from a bottle we often twist it back and forth. Overcoming friction in a roundy-cum-roundy direction also overcomes friction in an up and down direction.

There will be very little friction on the vertical axis since the compass is supported on a column of oil, and since the pump overcomes " up and down " friction, it also overcomes " roundy-cum-roundy " friction. The master compass card is fitted to the vertical ring and is carried round by the sensitive element.

34. The ballistic.—The ballistic consists of two working bottles which contain oil. The spinning wheel makes an air pressure which forces oil to the *high* side of the compass. The rotor runs in the opposite direction to the Sperry. The Brown rotor rotates clockwise when looking at the South end so that the weight of oil on the high side makes the compass North-seeking. The Brown compass is thus a bottom-heavy pendulum, whereas the Sperry is an inverted (top-heavy) pendulum.

35. Damping.—The eccentric pivot technique is not used and there is therefore no need for a phantom ring. The ballistic is hung from the sensitive element itself and damping is produced by applying an opposite torque about the vertical axis. The force being applied on a horizontal axis.

A second pair of oil bottles is fitted (see Figs. 42 and 43), and these include a fine needle valve (the damping valve) which only permits a very slow flow of oil. The air pressure produced by the spinning rotor wheel causes oil in the damping bottles to flow *slowly* to the *low* side.

It will be seen that the damping bottles are in opposition to the working bottles but their effect is, at first, very small because of the slow movement of the oil past the damping needle.

If the compass is started off the meridian, the end towards the East will tilt up and the working bottle on this end will fill, and the compass begin moving towards the meridian again. The slowly increasing opposite effect of the damping bottles will, however, slow up the compass as it approaches the meridian. As the compass crosses the meridian the slowing up is still more. When the compass begins to return to the meridian, having now acquired opposite, but less, tilt there will be oil in the high side of both the damping and working bottles. The weight on the high side will still further reduce the tilt with which the compass would otherwise have reached the meridian. In the N. hemisphere the settling point will be with the compass on the meridian with the N. end tilted up. Some excess oil will be in the N. bottle and this will cause a precession westwards at the same rate as the meridian is drifting westwards. Since the compass is on the meridian the tilt effect will be nil. In the S. hemisphere the settling point will be on the meridian with the South end tilted

up, and sufficient oil on the South-working bottle to produce a precession equal to the drift of the meridian Eastwards.

Whereas the damping in a Sperry compass is by a torque about the horizontal axis, the damping in the Brown is by an opposing torque about the vertical axis. This lengthens the actual period of the compass. The undamped period is still 84 mins. but the damped period is about 95 mins.

It will be observed that as damping is achieved by introducing an opposing precession in azimuth, the compass will settle in the meridian and there is no damping error. (Auxiliary latitude correction). The damping is arranged to be about 67%.

36. Latitude levelling device.—A latitude levelling dial is fitted to the rotor case on the West side. This dial carries an eccentric weight so that when it is set for latitude it makes the N. end or the S. end heavy so that the axis of the compass will not only settle on the meridian but will also be horizontal.

The latitude levelling dial can only be set when the compass is stopped or the compass would develop a large wander and take some time to settle out again. It should, therefore, be set for the middle latitude of the passage before leaving.

37. Latitude speed error.—There is no arrangement for correcting this but its value is tabulated in the service manual and it can be applied.

38. The follow-up system.—In order to operate the repeaters some means must be found of following the movement of the master compass without touching it. Around the compass is fitted a follow-up ring which consists of a large gear wheel fitted with three silver rings making a sliding contact with three brushes to complete electrical circuits. The follow-up ring is rotated by a step-by-step motor, the distributor for driving which is contained in a unit called the " controller," mounted on the switchboard. Fitted into the follow-up ring is the air vane. The air vane consists of two light paddles fitted to a vertical spindle which carries a T-shaped contact piece.

The spinning wheel blows a light blast of air through a radial jet mounted on the W. side of the vertical ring. If the air vane is exactly in line with the nozzle the jet of air blows through the centre one of three holes. Should the air vane be slightly to one side, however, the air jet will blow into one of the side holes. This air pressure will lift one of the paddles and so cause the T-shaped contact piece to make contact on one side.

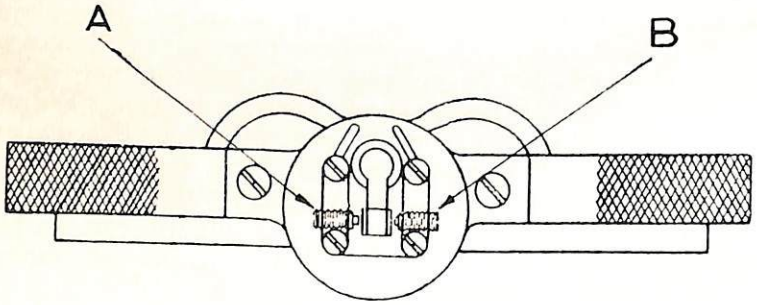


FIG. 35.

This completes an electric circuit to a valve amplifier which operates the change-over relay in the controller.

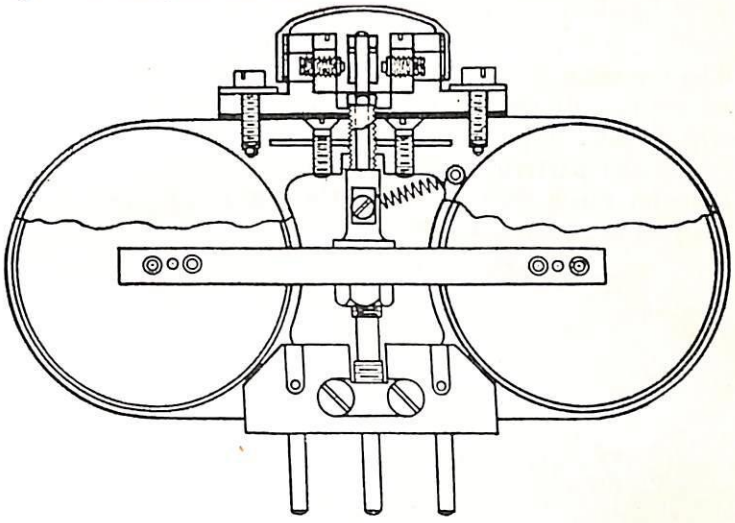


FIG. 36.—Sectional Drawing of Air Vane.

The controller contains an electric motor (A) the direction of rotation of which is reversed by the change-over relay (B). The shaft of this motor drives three cams which operate the three fingers of a distributor (C) and so energises the coils of the step-by-step motor which drives the follow-up ring. A second distributor (D) works the step-by-step motor in the repeaters and this incorporates a lost motion device (E).

The sequence of events is as follows :—Starting with the air vane in exact alignment with the air jet, suppose the ship (and the air vane) moves to the North. The air pressure will blow into the hole at the South side of the air vane and lift the paddle. This will make contact on one side of the contact piece in the air vane. This energises the change-over relay. This runs the motor ahead and the camshaft will insert the distributor contacts in the order 1, 2, 3—1, 2, 3. The coils of the step-by-

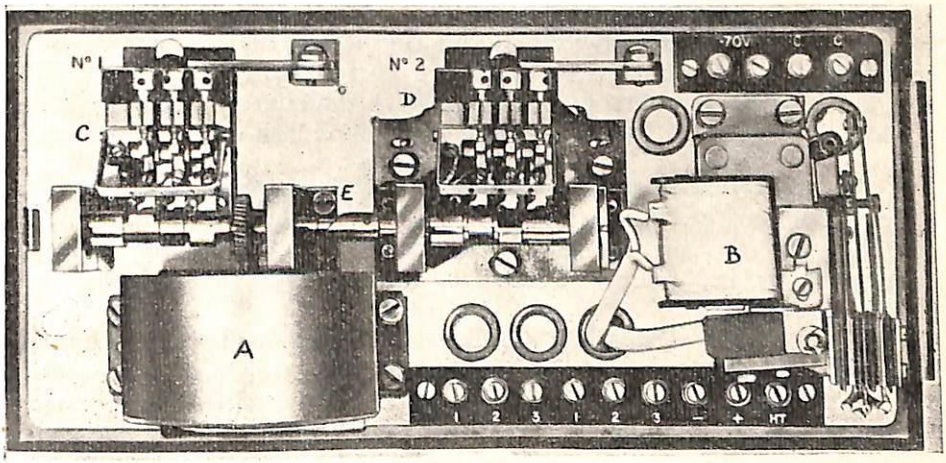


FIG. 37.

step motor will be energised in this order too. As the step-by-step motor rotates it will drive the follow-up ring to the South and so bring the air vane in front of the jet again. Momentum will carry the air vane across the jet. The other paddle will be lifted, making contact on the other side, and so releasing the change-over relay. This reverses the controller motor and the distributor fingers engage in the order 3, 2, 1—3, 2, 1 and so reverses the step-by-step motor.

In some older patterns the reversal of the camshaft was effected by a sun and planet mechanism, so that the controller motor could rotate continuously in the same direction.

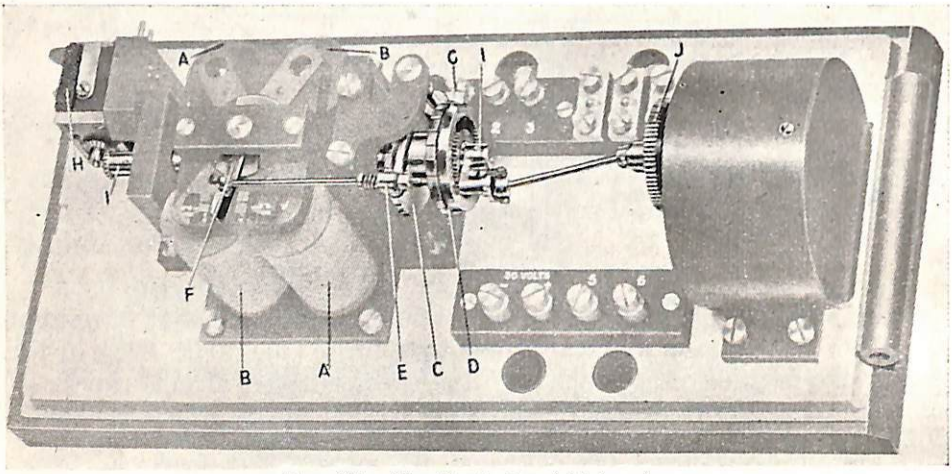


FIG. 38.—The Controller (old type).

39. Repeaters.—The distributor can also be made to energise the step-by-step motors of the repeaters. In recent models a second distributor is fitted with a lost motion device to eliminate hunt from the repeaters.

Instead of the air vane more recent compasses use an induction follow-up. The system consists of two inductances mounted on the limbs of a U polepiece carried on the vertical ring. Plugged into the follow-up ring (instead of the air vane) is a third inductance. If the follow-up inductance is exactly midway between the other two no current will be induced in it, but if it is not central a current will be induced. This signal current is amplified and used to drive the controller motor in such a way as to bring the follow-up inductance back to a central position.

40. Electrical arrangements.—A 50-volt battery of accumulators is floated across the ship's supply, which steadies the supply and will also run the gyro for a few hours in the case of a power failure. The precautions stated in " Munro's Electricity and the Magnetic Compass," § 46, should be taken.

No friction is permissible on the sensitive element, and to make a sliding contact on the stem head, for the driving power for the gyro wheel, mercury rings are fitted. The upper spindle is fitted with three iron rings, around these are three hollow iron rings filled with mercury. These rings are a clearance fit on the spindle and the mercury forms a cushion to float

the rings mechanically clear, and to make the necessary sliding electrical contact. The current is then carried down the vertical ring and steps across to the rotor case by three very thin uncovered wires. These wires must not touch each other nor the compass.

An alarm bell is sometimes fitted and this rings if the air vane follow-up system fails to work.

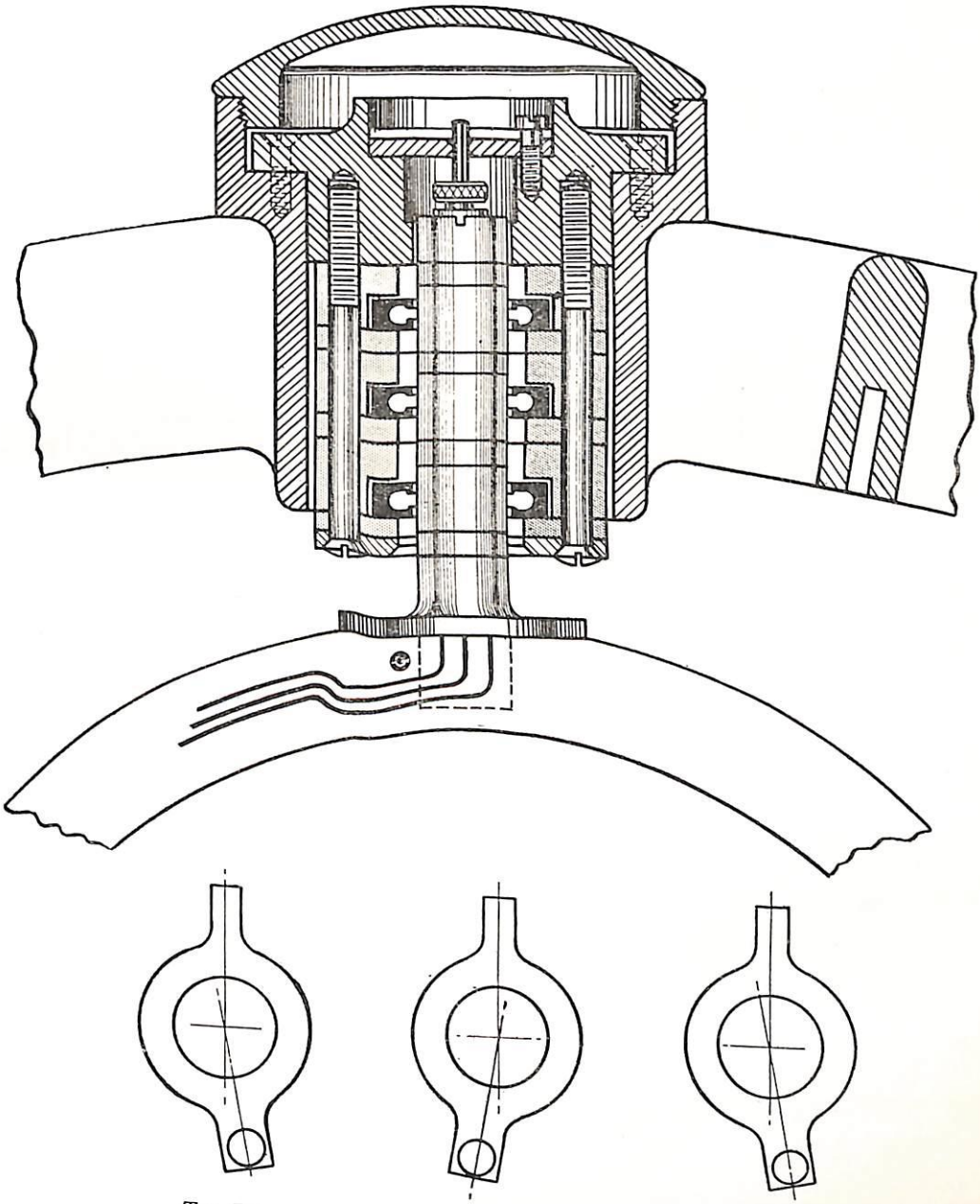


FIG. 39.—Section through Top Housing of Vertical Axis showing top of Vertical Axis and arrangement plan of Mercury Rings.

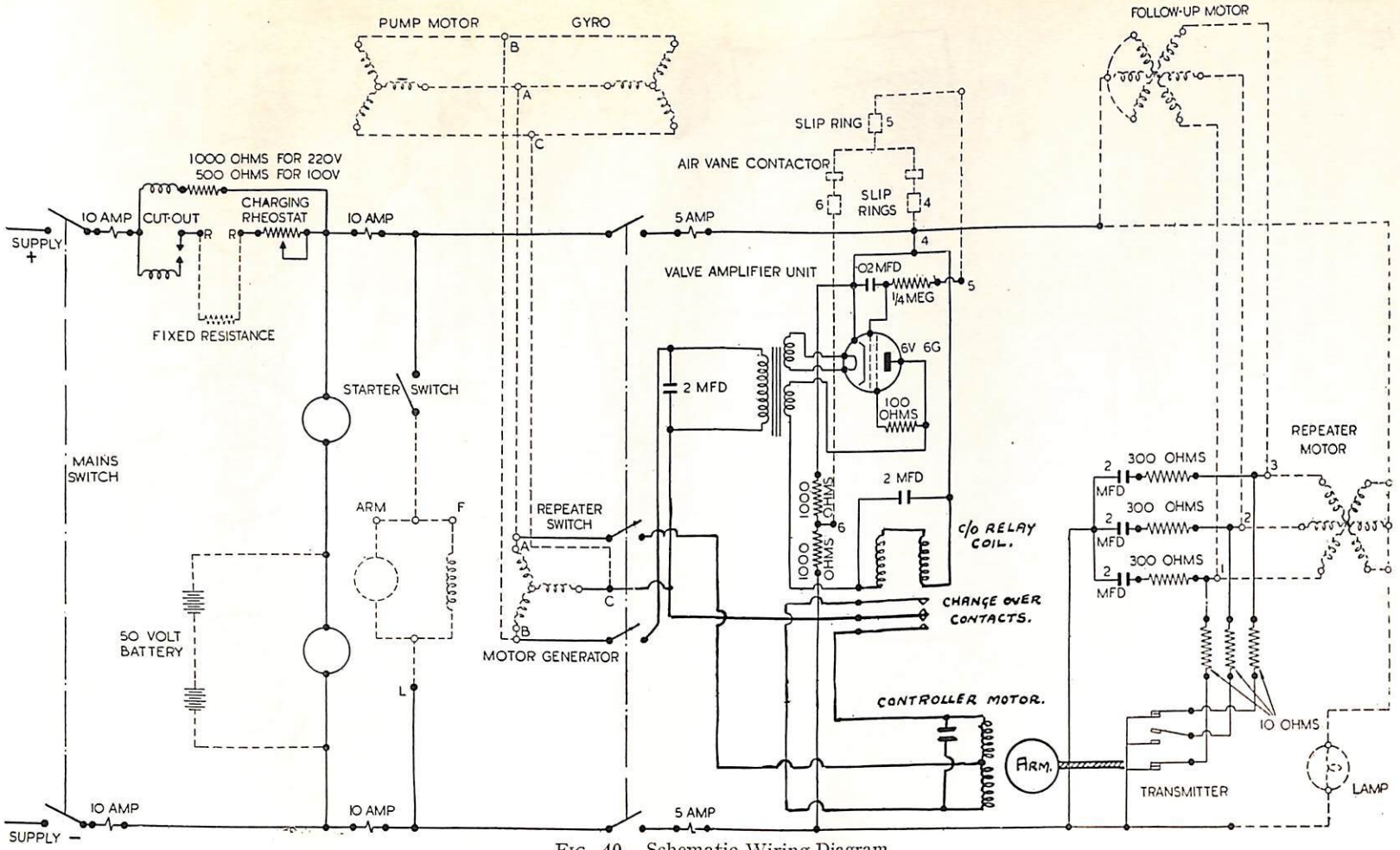
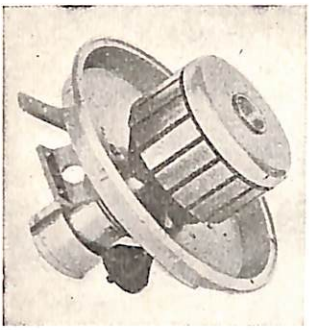
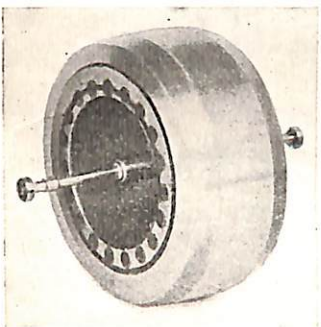


FIG. 40.—Schematic Wiring Diagram.



South end of Gyro wheel case, showing stator and case balance weight.



Gyro wheel and flexible shaft showing copper bars and spiral for ascertaining speed of wheel.

Centre ring and North end of Gyro wheel case showing air scoop, knife edge, and case balance weight.

FIG. 41.

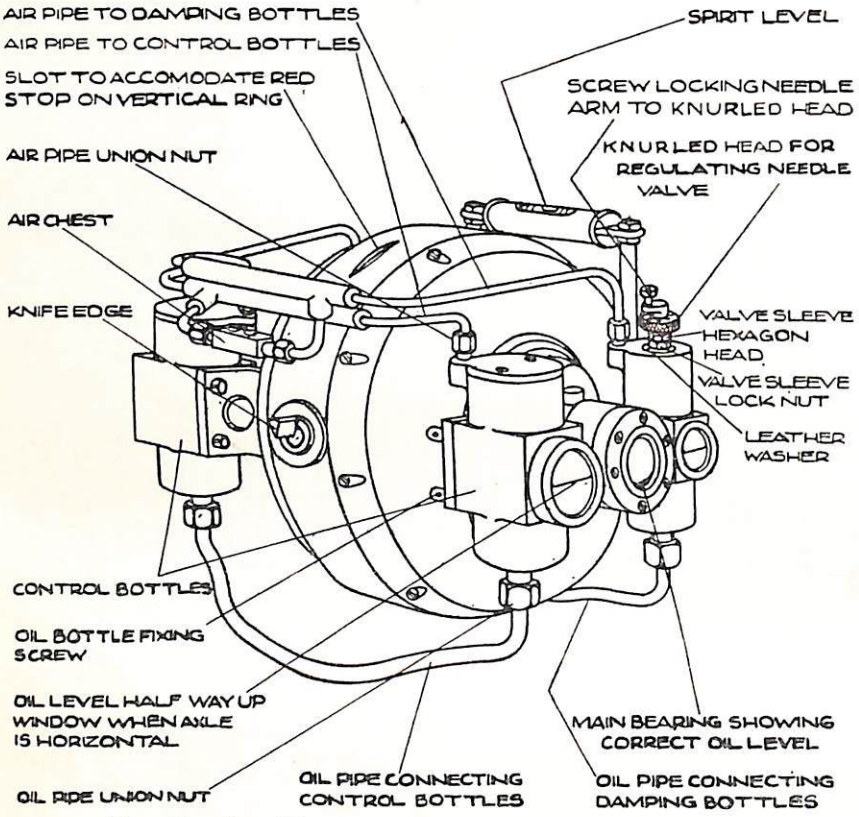

AIR PIPE TO DAMPING BOTTLES
AIR PIPE TO CONTROL BOTTLES
SLOT TO ACCOMODATE RED STOP ON VERTICAL RING
AIR PIPE UNION NUT
AIR CHEST
KNIFE EDGE
CONTROL BOTTLES
OIL BOTTLE FIXING SCREW
OIL LEVEL HALF WAY UP WINDOW WHEN AXLE IS HORIZONTAL
OIL RIDE UNION NUT
OIL PIPE CONNECTING CONTROL BOTTLES
SPIRIT LEVEL
SCREW LOCKING NEEDLE ARM TO KNURLED HEAD
KNURLED HEAD FOR REGULATING NEEDLE VALVE
VALVE SLEEVE HEXAGON HEAD
VALVE SLEEVE LOCK NUT
LEATHER WASHER
MAIN BEARING SHOWING CORRECT OIL LEVEL
OIL PIPE CONNECTING DAMPING BOTTLES

FIG. 42.—Gyro Wheel and Casing removed from vertical ring.

EXERCISE IV.

1. Describe how friction is eliminated on the vertical axis of the Brown gyro compass.

2. Why does the Brown gyro rotate in the opposite direction from the Sperry ?

3. State what are, in your opinion, the three most important differences between Brown and Sperry compasses.

4. Why is it not permissible to reset the Latitude Levelling dial at sea ?

5. Why has the Brown compass a damping valve ?

6. Trace the driving power from the terminal block to the rotor case.

7. Compare the effects of pushing round the card on a Brown and Sperry compass when the compasses are running.

8. What are the effects of wide variations in the supply voltage of the gyro compass ?

9. What care should be given to accumulators ?

10. Why is there no auxiliary latitude correction on the Brown compass ?

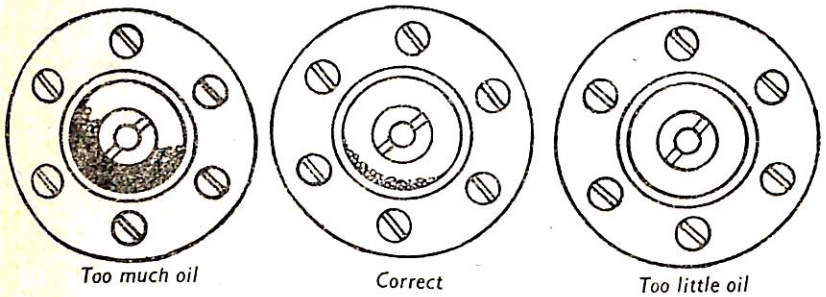


FIG. 43 (a).

Oiling the gyro wheel bearings need only be done about once in every two or three weeks. Open the lid of the binnacle and put six drops of oil in each of the oil holes at the ends of the gyro casing marked N. and S. When the wheel is spinning a thin film of oil should be just visible at the bottom edges of the glass windows at the ends of the bearings.

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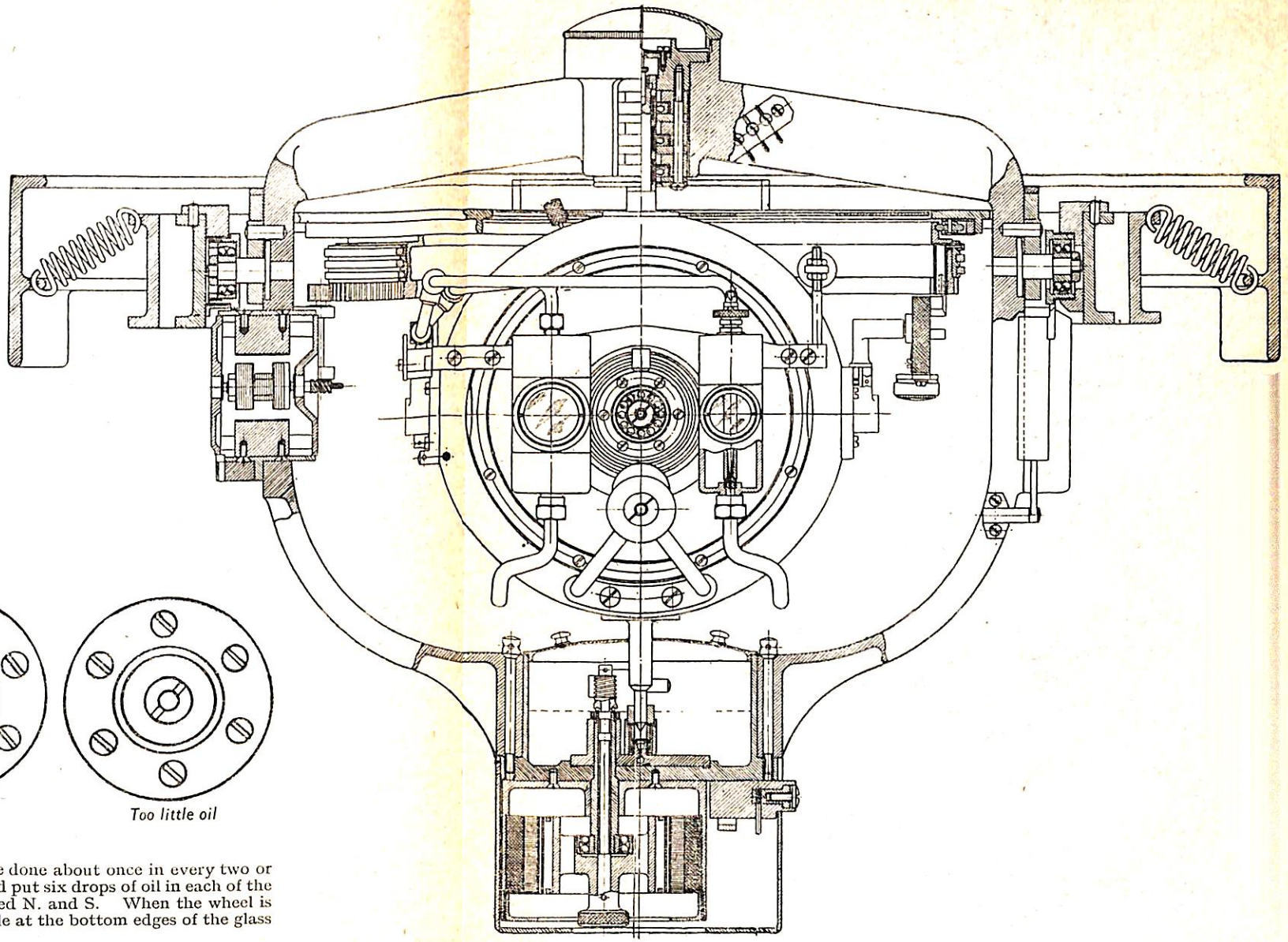


FIG. 43.

Too much oil

Oiling the gyro wheel bearing
three weeks. Open the lid of the
oil holes at the ends of the gyro c
spinning a thin film of oil should be
windows at the ends of the bearings

To face Page 15

CHAPTER V.

THE AUSCHÜTZ GYRO

41. Brief description.—The Auschutz compass is not fitted to many British ships and only a brief description is given here.

The sensitive element consists of a ball containing two gyroscopes. The ball has been exhausted of air and filled with hydrogen under high

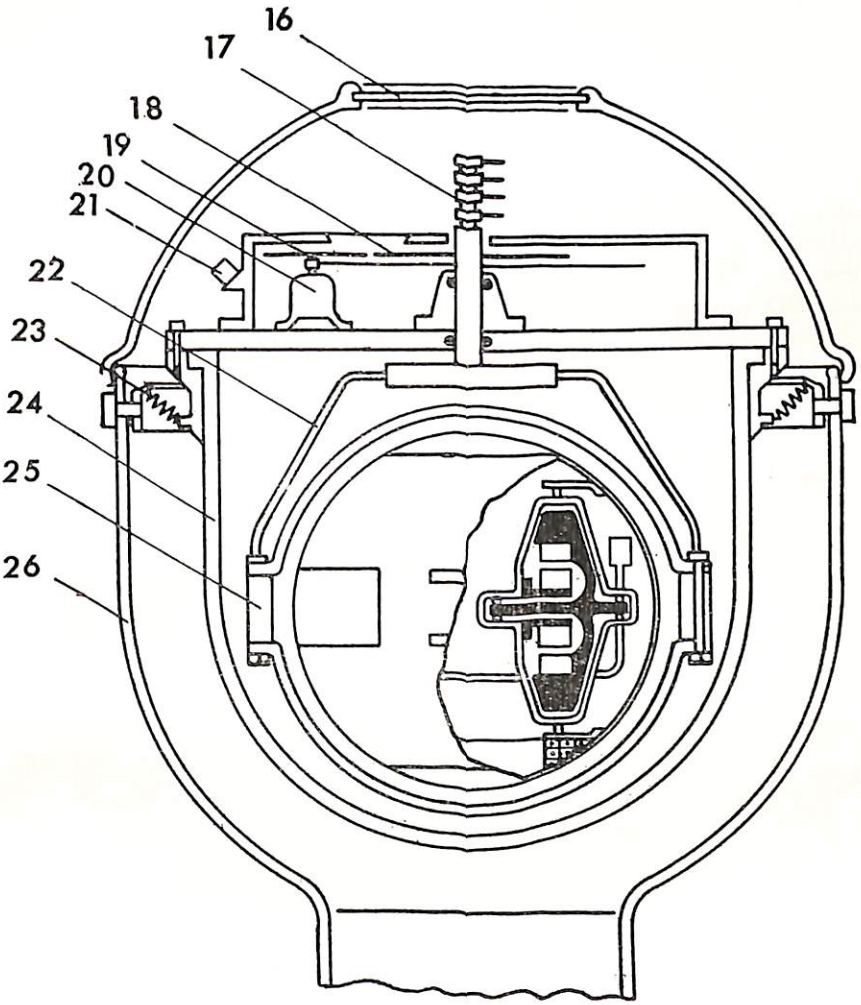


FIG. 44.—Auschütz Gyro Compass.

16. Glass Cover.
17. Rotating Bearings.
18. Card.
19. Vernier Card.
20. Follow up motor.
21. Terminals.
22. Supporting Arms.
23. Springs.
24. Glass Vessel.
25. Glass ring on outer sphere.
26. Binnacle.

pressure. In this way the oil supply inside can neither evaporate nor oxidise. No unauthorised person can open the ball. The gyro system is pendulous and therefore North-seeking. Damping is by oil flowing in oil bottles. The compass, like the Brown, is bottom heavy pendulous, whilst the Sperry behaves as if it were a top-heavy pendulum.

The outside of the Auschütz ball is quite smooth and non-conducting except for some inlaid graphite rings which collect the electrical current. This ball is contained loosely in an outer sphere and the whole assembly is completely submerged in acidulated water which is contained inside the glass-lined binnacle. The specific gravity of the inner ball is actually slightly greater than that of the liquid. Both inner and outer balls are however fitted with coils arranged so that their fields repel. By this means the inner ball is always maintained in the central position and no matter how much the ship rolls it will not come into contact with any other part of the system. It is thus quite free to turn, apart from skin friction with the liquid which is very slight.

The current necessary to run the gyro wheels is transmitted through the acidulated liquid to the graphite collecting rings. Some degree of short circuiting will take place, electrolysis is avoided by using only A.C. currents.

The follow-up system works on the principle of the Wheatstone bridge (see " Munro's Electricity and the Magnetic Compass, § 25) and is smooth and continuous. The repeaters are self-synchronising, that is, they do not require re-setting, and can be made to read to an accuracy of $\frac{1}{10}$ degree.

Large changes of temperature would affect the specific gravity of the liquid and after the level at which the inner sphere floats. The compass is fitted with a thermostatically-controlled cooling system, and an alarm sounds if this fails to keep the temperature within the prescribed limits.

The compass requires virtually no maintenance on board ship beyond switching on or off.

CHAPTER VI.

A.C. CIRCUITS

42. Alternating voltages.—In "Munro's Electricity and the Magnetic Compass" it was pointed out that unless a commutator is fitted to a generator the resultant voltage will be A.C., and frequently reversing in direction. The frequency of an A.C. voltage is the number of times per second that the voltage goes through a complete cycle. Such an alternating voltage can be represented by a curve, Fig. 45 (a).

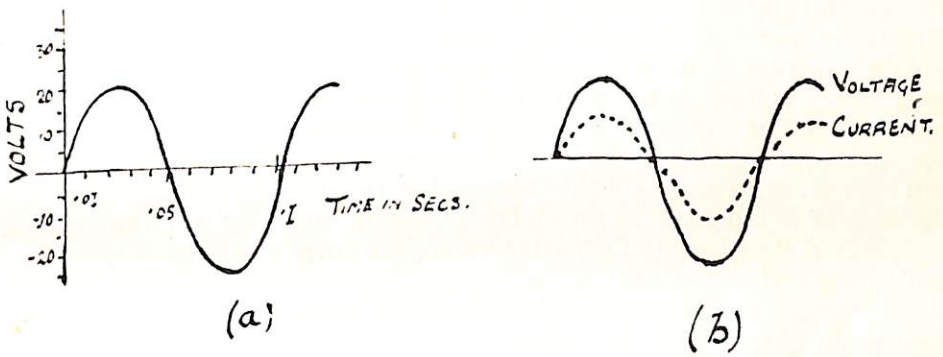


FIG. 45.

The curve depicts the voltage plotted against time, that is, it is drawn on a time base. Since it takes $\frac{1}{10}$ second for the cycle to be completed, the frequency is 10 cycles per second. The frequency of most A.C. voltages is much higher than this.

43. Circuits with resistance only.—If an A.C. circuit contains only resistance then Ohm's law will apply and at any instant the current will be proportional to the voltage, Fig. 45 (b). The current is in step with the voltage, they both achieve a maximum at the same time. They are said to be "in phase."

44. Effect of inductance.—If current is switched on to an inductance coil, a magnetic field is set up in the inductance, this requires work, and so the rise in the current will be opposed—that is the inductance sets up a back E.M.F.

Similarly if the current into the inductance is dying away the magnetic field will be collapsing and so releases energy which will endeavour to maintain the current and oppose the change in its value.

With A.C. currents the inductance imposes a limitation on the value of the current which can pass. (See "Munro's Electricity and the Magnetic Compass," § 84.)

An inductance of one henry is such that a voltage of one volt will cause the current through the inductance to rise at the rate of one amp per second.

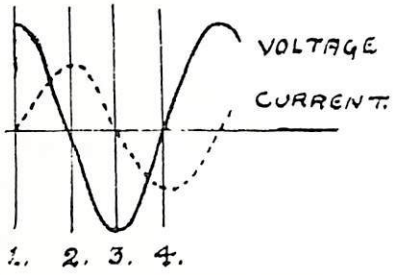


FIG. 46.

In starting with voltage maximum, Fig. 46 (position 1), the rate of growth of current through the inductance will be maximum. After $\frac{1}{4}$ cycle (position 2), however, the voltage has fallen to zero, the current has been steadily growing through the inductance so long as the voltage was positive, and it has now reached its maximum value. As the voltage becomes negative the current will not be reversed, the inductance will still endeavour to maintain the current, but the negative voltage will cause the current to fall until, at the end of $\frac{1}{2}$ cycle (position 3), when the voltage has reached its maximum negative value, the current will be stopped. It will be seen that the current is not in phase with the applied voltage. It achieves its maximum value $\frac{1}{4}$ cycle after the voltage reaches maximum. That is the current lags the voltage by 90°. The current is greatest when the voltage is changing most quickly (at mean position when voltage is zero) and the current is always directed to the last peak of the voltage.

Alternating voltages and currents can be expressed in vector diagrams as in Fig. 47 (a). Angles usually being reckoned anti-clockwise.

45. Resistance and inductance together.—When there is resistance and inductance together in a circuit the applied voltage will have to do two things :—

1. Overcome the resistance.
2. Overcome the back E.M.F. of the inductance The resultant current will be less than if there had been resistance alone, and will lag the applied voltage by some angle from 0° to 90°.

The resisting effect of the inductance is called the inductive reactance. The reactance in ohms $= 2\pi f L$ where f is the frequency in cycles per second and L is the value of the inductance in henries. The total effect of reactance and resistance is called the impedance of the circuit, and since resistance and reactance are 90° to each other, then :—

$$\text{Impedance} = \sqrt{(\text{resistance})^2 + (\text{reactance})^2}.$$

46. Capacity.—When a voltage is applied to a condenser, the condenser becomes charged. The law is $Q = CV$ where Q is the charge in coulombs, C the capacity of the condenser in farads, and V the applied voltage. If the applied voltage changes then the charge must change and this will involve the flow of a current.

In Fig. 47 (b) we can see that as the applied voltage changes so does the charge on the condenser. Now at position 1 the charge is increasing rapidly so that a large current is necessary to supply it. At position 2 where the charge has achieved a maximum it is momentarily steady and no current is necessary. At 3 the charge has become zero and this decrease in charge has necessitated a negative current.

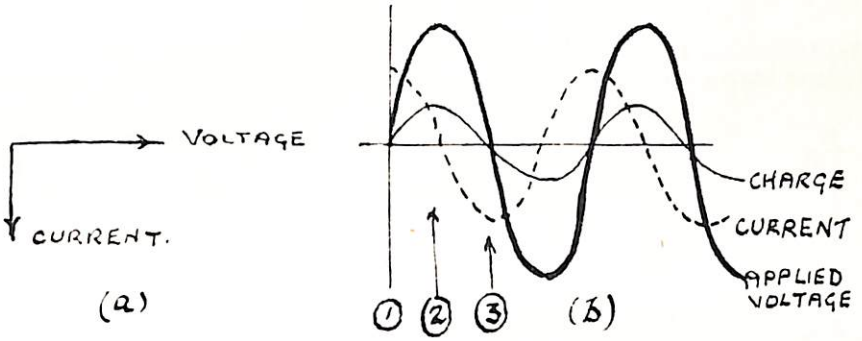


FIG. 47.

The current is 90° out of phase with the applied voltage but in this case it leads the voltage by 90°. The current is greatest when the change of voltage is greatest (when voltage is zero) and is always directed towards the next peak of the voltage. The resistance effect of the condenser is called the capacitive reactance and its value in ohms is $\frac{1}{2\pi fC}$ (f in c.p.s C in farads).

Notice that since $Q = CV$, if the condenser has a high capacity it will acquire a high charge from a given voltage. If the frequency is also high the time available in which to build up this high charge is very short and a big current will be necessary, consequently the reactance must be small. That is the reactance varies *inversely* as the capacity and the frequency.

In the case of inductance, if the inductance is big the rise in the current will be slow, and if the frequency is high this slow increase will last for only a brief interval of time. So a high inductance and high frequency will give a small current, and hence a high reactance. Reactance then varies *directly* as the inductance and the frequency.

47. L.C. circuits.—An L.C. circuit is one which contains inductance and capacity. In a circuit which contains resistance too then the applied voltage, driving a current through the circuit, may be considered in three parts.

1. A voltage E_1 overcoming the resistance, and in phase with the current. $E_1 = IR$.

2. A voltage $E_2 = 2\pi fLI$ overcoming the inductive reactance and lagging the current by 90°.

3. A voltage $E_3 = \frac{1}{2\pi fC} I$ to overcome the capacitive reactance and leading the current by 90°. These voltages can be represented in a vector diagram, Fig. 48 (a).

48. Resonance.—Now if $2\pi fL = \frac{1}{2\pi fC}$, E_2 and E_3 are equal and since they are opposite they will cancel out. The impedance will, in this case, be equal to the resistance alone, which is the smallest possible value it could have and so the current will be a maximum.

If $2\pi fL = \frac{1}{2\pi fC}$ then $(2\pi f)(2\pi f) = \frac{1}{LC}$ and $2\pi f = \frac{1}{\sqrt{LC}}$, $f = \frac{1}{2\pi\sqrt{LC}}$

This is called the resonant frequency and a given voltage of this frequency will cause bigger currents than any similar voltage of a different frequency.

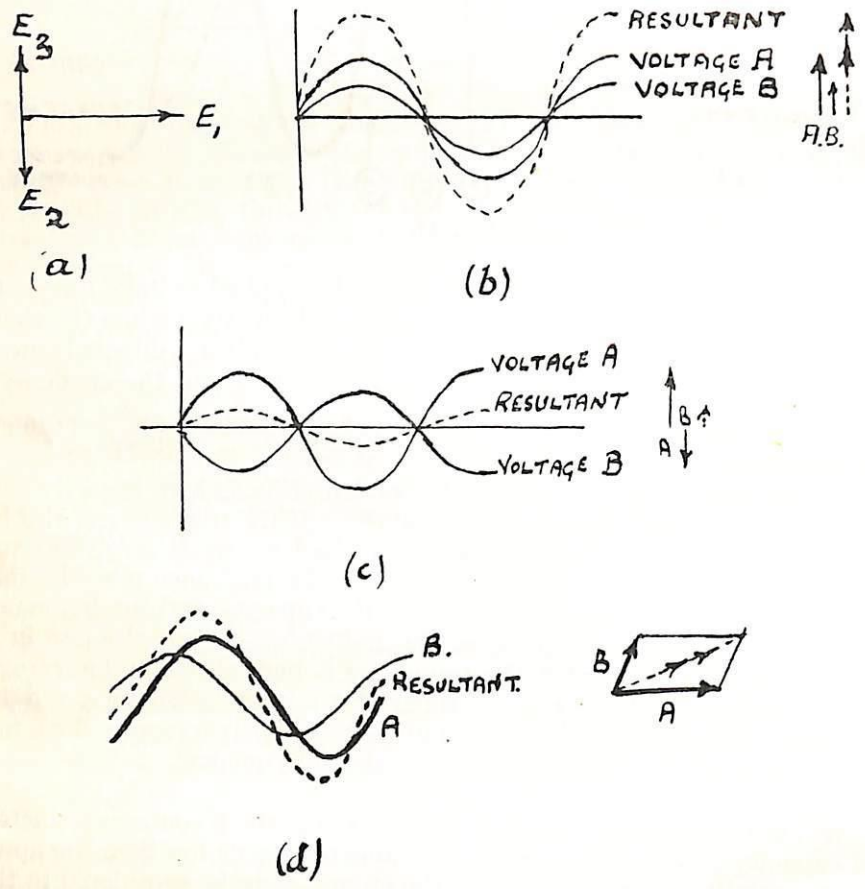


FIG. 48.

49. Other cases.—We have considered the phasing of voltage and current in various A.C. circuits, but it should be realised that, in some cases, we will have to consider two voltages, or two currents, of different phase.

If two A.C. voltages are exactly in phase they will add together, Fig. 48 (b), if they are in anti-phase (180° out of phase) they will subtract from each other, Fig. 48 (c). At any intermediate position the resultant voltage can be found by a vector diagram.

If two voltages of slightly different frequencies are superimposed, they will sometimes be in phase, and sometimes out of phase. When they are in phase the resultant voltage will be high, and when they are in anti-phase it will be low. The number of times the two voltages get exactly into step is called the " beat frequency " and is equal to the difference between the other two frequencies.

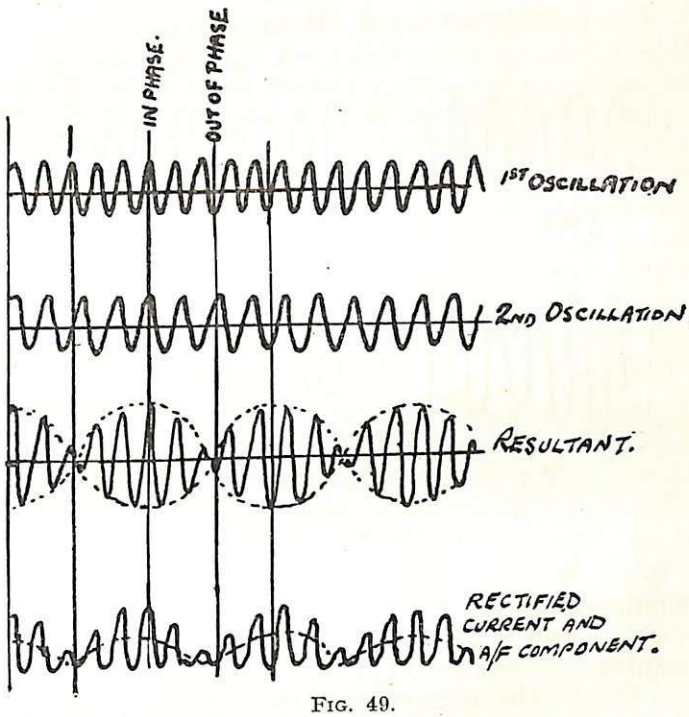


FIG. 49.

50. Kinds of oscillations.—An oscillation with the same amplitude all the time is called a " continuous wave," Fig. 50 (a).

An oscillation which " dies away " is a damped wave, Fig. 50 (b).

The frequency of the electro-magnetic waves which are usually referred to as radio waves is from about 10 kilocycles per second to 10^9 kilocycles per second. Such waves are referred to as R/F (radio-frequency) oscillations.

Sound waves are of an entirely different nature from electro-magnetic waves and their frequency is from 16 cycles to about 20,000 cycles per second (*i.e.* 20 kilocycles) but most distinct sounds fall in the range of 800 to 3000 cycles per second. Such oscillations are A/F (audio-frequency).

An R/F oscillation cannot be made audible directly because :—

1. The diaphragm of an earpiece cannot vibrate much faster than the audio range.

2. Even if the diaphragm could vibrate at R/F the ear could not detect the vibrations.

3. The induction coil in an earpiece would have a high impedence at high frequencies (§ 45).

The R/F oscillation must have an audio frequency oscillation superimposed upon it, it is then said to be " modulated," Fig. 50 (c). The mean value of such a wave form, however, is zero and some means must be found to detect the modulations. To do this, all or part of the vibrations on one side are supressed, 50 (d), this is called " detection." When one half of an alternating current is supressed, leaving a series of pulses all in the same direction, that is a D.C., the action is called rectification, and detection differs little from rectification but the latter term is used when changing A.C. into D.C.

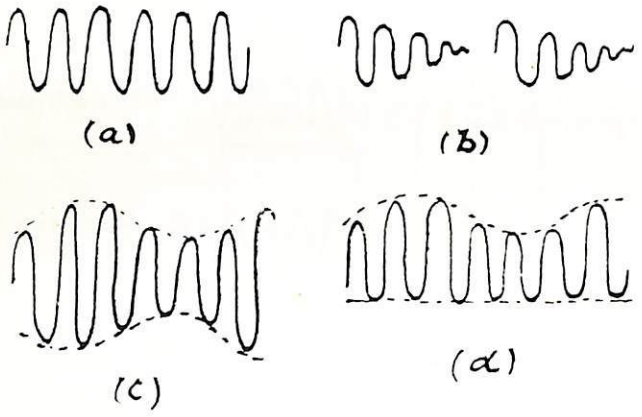


FIG. 50.

When continuous waves (C.W.) are used there is no A/F component in the wave, and all that would be heard, for a dash would be a click at the beginning, another click at the end as the diaphragm of the earpiece took up its new position for the mean value of the detected wave. In order to produce an A/F oscillation it is necessary to superimpose a second frequency so that the beat frequency between the two will be audible, this is called " heterodyning." (See Fig. 49.)

EXERCISE VI.

1. Draw rough curves on a time base to show two voltages 90° out of phase.

2. Discuss the effects of inductance and capacity on the phase of A.C. currents.

3. What is an L.C. circuit ?

4. What is meant by resonant frequency ?

5. Describe " modulation," " detection," " amplification."

6. Does Ohm's law apply to an A.C. circuit ?

CHAPTER VII.

THERMIONIC VALVES

51. Thermionic emission.—In a good conductor there are a number of mobile electrons which are always moving from one atom to another. When the substance is heated the movement of these electrons is increased, until at high temperatures some of them leave the surface of the material.

When the electrons have been emitted they will not normally escape altogether, but will be attracted by the positive charge they left behind. Thus when a conductor is heated above a certain temperature it will be surrounded by a cloud of electrons called a " space charge." If, however, there is a positively charged " plate " introduced the negative electrons will be attracted to it.

The emitting material is called the " cathode " and the collecting plate the " anode."

52. The cathode.—The cathode can be heated by passing an electric current through it or can be indirectly heated by a heating wire inside the cathode which is then in the form of a thin tube. Most cathodes consist of a metal wire coated with certain oxides which are particularly good emitters of electrons. Indirectly heated cathodes are used when A.C. current is employed for heating, if A.C. is used for a directly-heated cathode the fluctuations generally produce a hum, but since considerable power is required for indirect heating it is not suitable where the heating current is drawn from batteries.

53. The anode is often made of nickel. In small valves it has to deal with only a small current, but in large valves it must be designed to stand the heat generated by a strong bombardment of electrons.

54. The envelope.—The envelope, usually of glass or silica, is often exhausted of air. When the interior is as near a vacuum as possible the valve is called a " hard " valve. For some purposes small traces of an inert gas are introduced into the envelope. Such valves are called " soft " valves. When a stream of electrons passes through a soft valve the electrons collide with the molecules of the gas and detach electrons, the gas is thereby " ionised." (See " Munro's Electricity and the Magnetic Compass," § 5.) The ionised gas lights up with a colour characteristic of the gas (neon tubes are an example). The positive ions are attracted to the cathode and the negative ions augment the flow of bombarding electrons.

If the vacuum of a hard valve falls it is said to have become " soft."

55. The diode.—A valve with only a cathode (directly or indirectly heated) and an anode is called a diode. If the anode is positive electrons emitted from the hot cathode will flow across the valve, the valve is said

to conduct. If the anode is negative, however, it will repel electrons and the valve will not conduct. Notice that we are talking about the flow of electrons not about the conventional flow of current. (See "Munro's Electricity and the Magnetic Compass," § 5.)

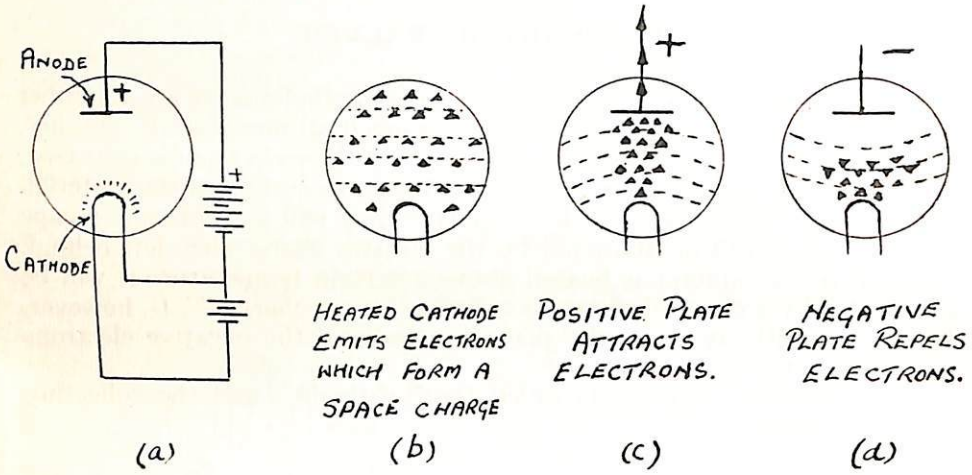


FIG. 51.

Fig. 51 (a) shows a diode valve. In Fig. 51 (b) is depicted the space charge produced by the heated cathode. In (c) the anode has positive charge and is attracting the electrons (the dotted lines attempt to show

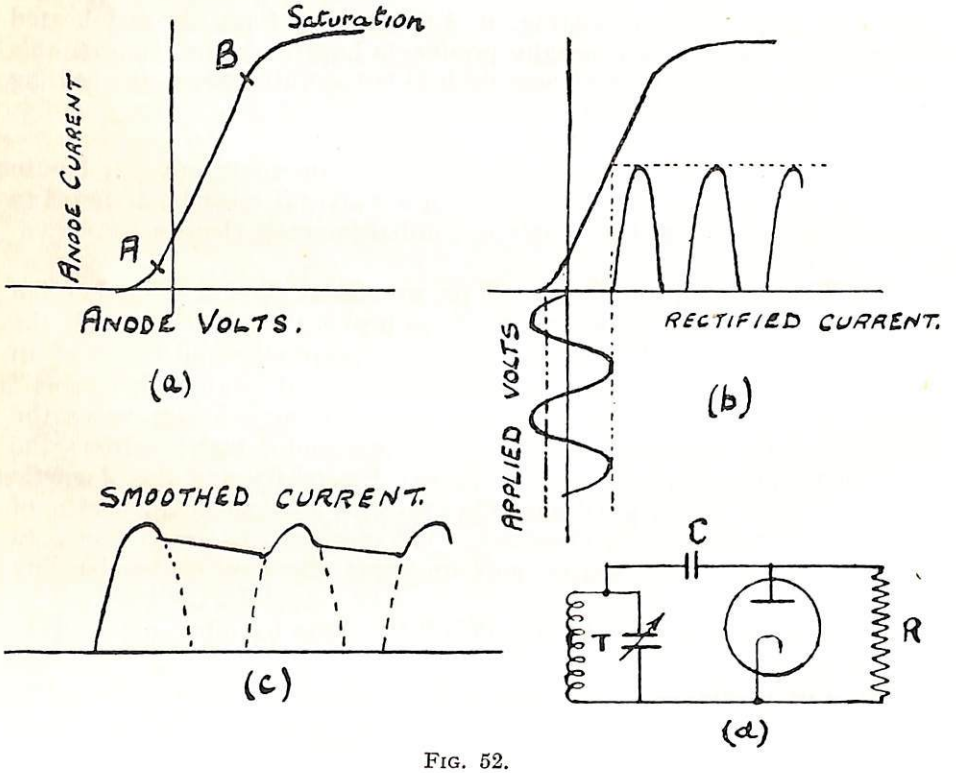


FIG. 52.

the attracting force). Current is now flowing in the outside circuit. In (a) the anode has negative charge and the valve is not conducting. The valve is thus a one-way valve.

56. Characteristic curves.—A graph can be drawn to show how much current flows in the anode circuit as the anode voltage changes.

Notice that between A and B in Fig. 52 (a) the graph is almost a straight line. When the anode is made sufficiently positive it will attract all the electrons emitted by the cathode. Any further increase in the anode voltage would not result in increased current. The valve is said to be saturated.

57. The diode as a rectifier.—Since a diode valve will only allow current to pass through in one direction it can be used as a " rectifier " or " detector." In Fig. 52 (b) is pictured the resultant short pulses of D.C., one half (or nearly one half) of the A.C. wave having been suppressed. The resultant D.C. current can be smoothed by a smoothing circuit (or filter) containing condensers and inductances to form shown in 52 (c).

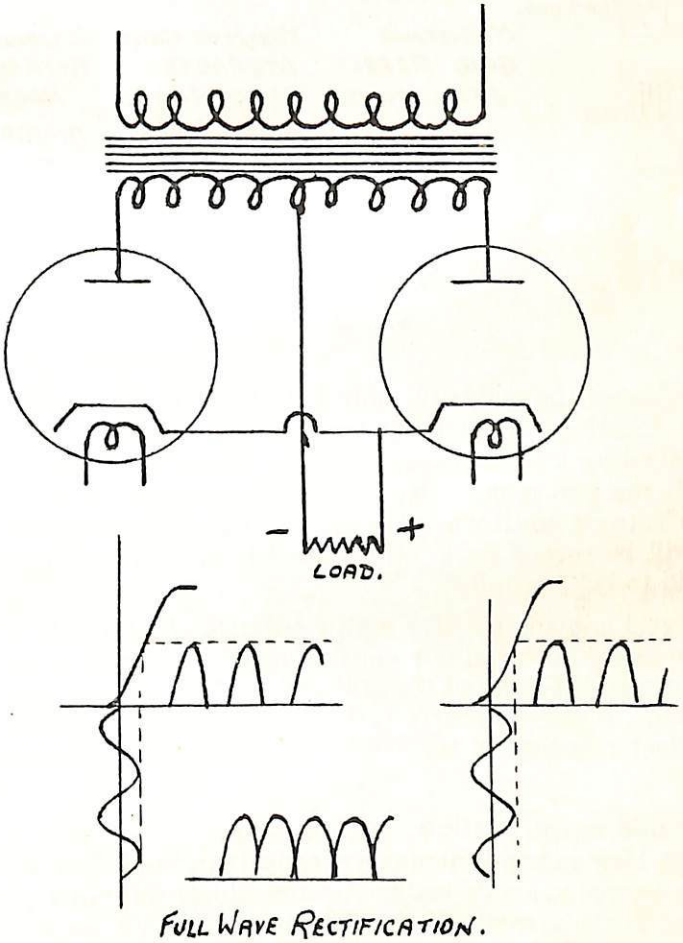


FIG. 53.

58. Full wave rectification.—In Fig. 53 we show a circuit using two diodes (the valves shown have indirectly heated cathodes). One valve will pass one half of the wave and the other will pass the other half wave, the resultant current is a full wave rectified current.

59. The triode.—If a third element called a grid is inserted between the cathode and the anode the valve becomes a triode. The grid consists of an open spiral or net of wire through which the electrons emitted from the cathode can readily pass.

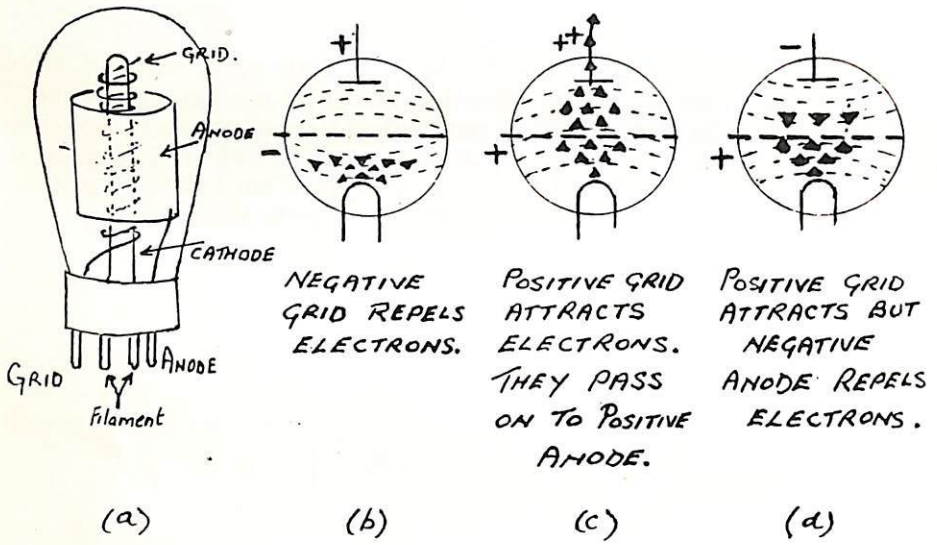


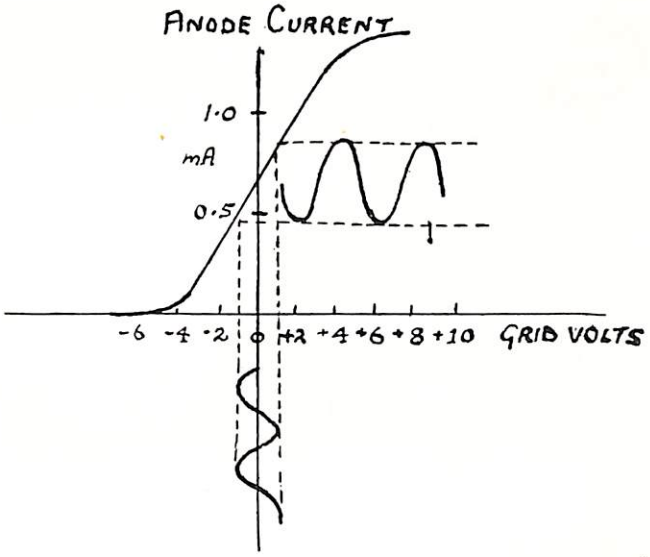
FIG. 54.

The object of the grid is to control the flow of anode current. When the grid is negative (with respect to the cathode) some of the electrons will be repelled back to the cathode, with a consequent drop in the anode current. If the grid is made more and more negative it will repel more and more electrons, until when the grid is sufficiently negative all of the electrons will be turned back. There will be no anode current and the valve is said to be "cut-off."

If the grid is made positive with respect to the cathode it will draw electrons from the cathode, but most of these, travelling at great speed, will pass through the holes of the grid and pass on to the higher potential of the anode. If the grid were to become sufficiently positive it would act as a collector instead of the anode and large grid currents would flow.

60. Triode amplification.—A small change in the grid voltage will cause a much bigger change in anode current than would have been caused by a similar change in anode voltage because the grid is much closer to the cathode than is the anode. If the straight part of the curve is used the amplified current will be an exact replica of the impressed voltage.

61. Triode detection.—The grid and cathode of a triode constitute a diode, and so the grid voltage is rectified, and it is then amplified in the anode circuit. One circuit of a triode amplifier is shown in Fig. 51 (a). This circuit is very similar to the one for a diode rectifier in Fig. 52 (d). R is the resistance across which the voltages at the modulating frequency will be manifest, C is a condenser to by-pass any remaining R/F, T is the tuned input circuit.



FIGI. 55.

62. The tetrode.—Each element in a valve forms the plate of a small condenser. In some cases this leads to instability so a fourth element, a " screen grid " is inserted between the cathode and grid. The screen grid is operated at a positive potential.

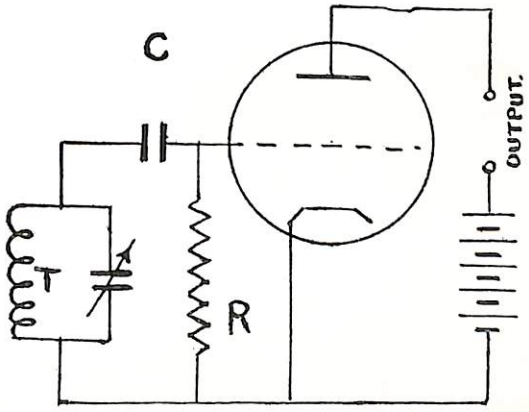


FIG. 56a.

63. The pentode.—The stream of electrons impinging on the anode will often result in electrons being knocked out of the anode, so causing " secondary emission." In the pentode a third grid called a " supression grid " is introduced to prevent this.

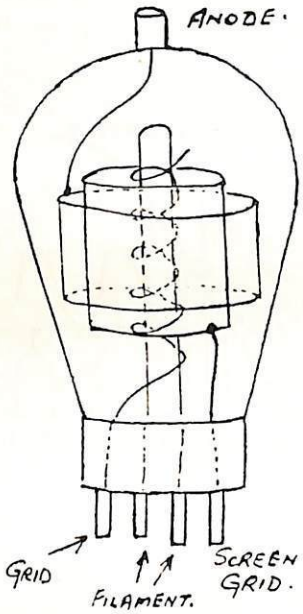


FIG. 56b.

64. The triode oscillator.—The oscillatory circuit was briefly referred to in " Munro's Electricity and the Magnetic Compass," § 103. The circuit referred to there consisted of a condenser in series with an inductance and a spark gap. The spark gap simply serves as a means of introducing and isolating energy in the circuit.

A mechanical analogy may make the circuit easier to understand. Suppose a weight is attached to a spring as shown in Fig. 57 (a). If the

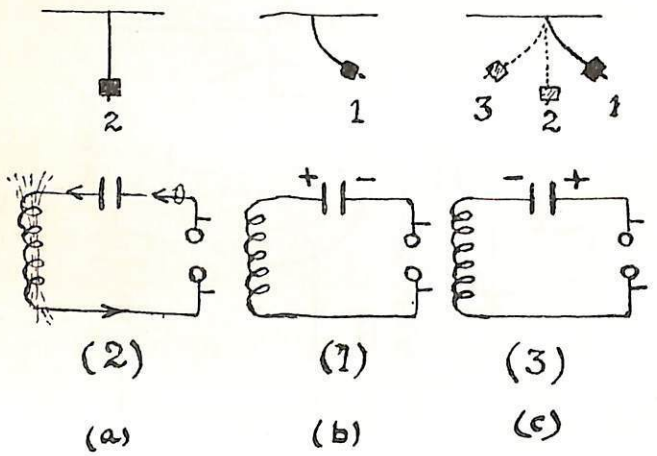


FIG. 57.

weight is pulled to one side (b) energy is introduced and is stored in the spring. If the weight is now released the spring will vibrate (c). At position 1 energy is stored in the spring (potential energy). At position 2 the spring is straight, it has given its energy to the weight. The weight now possesses energy by virtue of its motion (kinetic energy) and will continue to move bending the spring again, until at position 3 the weight has come to rest and the energy is once again stored as potential energy in the spring. The vibration will slowly die away as energy is lost in various frictional losses. A short stiff spring with a small weight will oscillate much more rapidly than a long weak spring with a heavy weight.

In the electrical case the condenser serves the same function as the spring, the inductance corresponds to the mass of the weight, the charge on the condenser is analogous to the compression of the spring, and the current corresponds to the velocity of the weight.

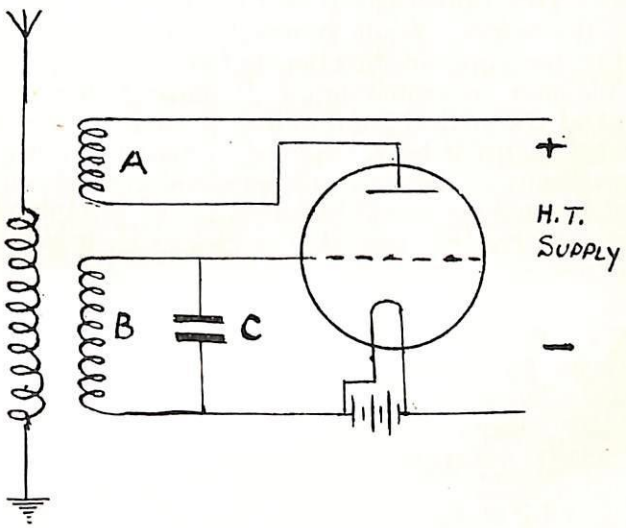


FIG. 58.

Suppose energy is introduced into the circuit by charging the condenser (position 1). If the spark gap is set to the correct width the maximum voltage set up by the charged condenser will be sufficient to break down the insulation of the air. A spark will leap the gap, the air becoming ionised will be a conductor. (See " Munro's Electricity and the Magnetic Compass.") The weight has been released. As current rises a magnetic field will build up around the inductance. By the time the P.D. across the condenser is zero all of the energy will be stored in the magnetic field (position 2). As the magnetic field collapses it will produce an e.m.f. in such a direction as to maintain the current in the same direction. By the time the magnetic field has entirely collapsed, the condenser will be charged again but with reversed polarity (position 3). Energy will be lost overcoming the resistance of the circuit and the oscillations will die away, they will be damped oscillations.

If we wish to maintain an undamped oscillation (a continuous wave) we must find some means of renewing the energy in the circuit.

Consider the circuit shown in Fig. 58. The positive terminal of the high-tension (H.T.) supply is connected to the anode through the inductance coil A.

When electrons from the space charge around the cathode flow to the anode they will cause a slowly increasing current through the inductance A. From Lenz's Law ("Munro's Electricity and the Magnetic Compass, § 57), since both coils are wound in the same direction this will cause a flow of electrons downwards in B. As this draws electrons away from the grid the latter will become more positive and so increase the current through the valve. The condenser C will become more positively charged on the upper plate.

At first glance it would appear that since a current in the valve has caused a bigger current in the valve, then a kind of vicious spiral has been set up. The anode current however overshoots its steady value and then begins to fall. This causes electrons to move down (A) and up (B). condenser (C) discharges. Again it would seem that we have started a vicious spiral in the opposite direction but the process is repeated again and again. We have an oscillating (or alternating) current, which gets a "leg up" just at the critical point and so prevents the amplitude dying away—the extra energy is being supplied by the H.T. battery.

The system can be likened to the mechanism of a pendulum clock. The energy of the main spring is imparted to the pendulum through the escapement which gives the pendulum a kick at each half swing and so keeps it swinging.

65. The amplifying valve in the "Brown" gyro.—A valve amplifier has been introduced to reduce the current in the air-vane circuit, thus materially adding to the reliability of the repeater system and eliminating the previously required frequent cleaning of the air-vane contacts. These now normally operate for many hundreds of hours without attention (see § 38).

The full circuit is shown in Fig. 40, a part of the valve circuit is given here.

The controller motor is a split-field motor, that is, it has two field windings which are wound in opposite directions. If one is energised the motor will run ahead, if the other is energised the motor runs astern. The change from one field winding to the other is effected by the change-over relay (Fig. 38). If the valve in the amplifier passes current the coil in the change-over relay is energised and this pulls the switch arm up.

In Fig. 59 the transformer T supplies the heater current and also the positive charge for the anode. Notice that the valve is a tetrode, and contains a cathode (indirectly heated) two grids and an anode.

If the air vane is contacting on one side, 5 and 6 are connected and this connects the grid to the centre tapping of the 200 Ω resistance which stands across the 50 v. supply line. The grid is thus made about 25 v. negative to the cathode and the valve will not pass current (or will pass very little). The controller motor is running ahead and drives the air vane across the air jet. The other side of the air vane contacts and joins 4 and 5. The grid is now at the same potential as the cathode and the valve passes current. The transformer feeds the valve with 230 v. A.C. but since the

valve acts as a rectifier only D.C. is passed and this flows through the windings of the change-over relay (any stray A.C. is passed through the 2-m.f.d. condenser). When the windings of the relay are energised the change-over switch arm is pulled up, the controller motor runs astern and the air vane is driven the other way.

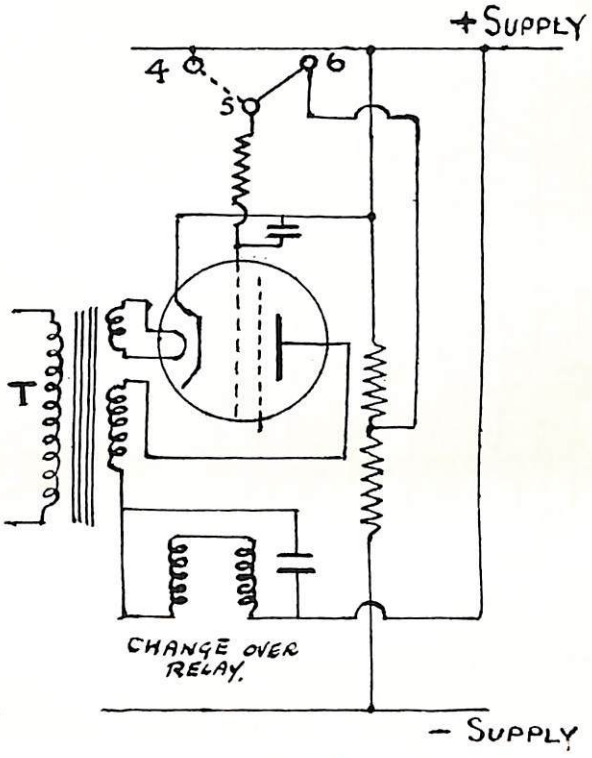


FIG. 59.

66. Amplification in Kelvin Hughes echo sounder.—Fig. 60 shows only parts of the circuit.

The two valves are pentodes. The signal from the receiver comes to the primary winding of the input transformer. The secondary winding of this connects to the grid of the first valve, the anode of which is carried to the grid of the second valve.

The anode current of the second valve energises the primary of the output transformer. The A.C. current in the output secondary windings is rectified in a Westinghouse rectifier and the resultant D.C. is used for marking the paper.

Part of this circuit is very interesting. It is an automatic control of the degree of amplification known as the "initial suppressor." The signal returned from shallow water is much stronger than the signal returned in deep water, therefore less amplification is necessary in shallow water, where the signal is returned very quickly.

To achieve this it is arranged that when the transmitting switch S closes to send out a signal the condenser C gives negative bias to the grid of the first valve, but the charge on C will slowly leak away through the resistance R and the negative bias on the first grid will slowly fade, and so the amplification factor of the first valve will increase as time passes.

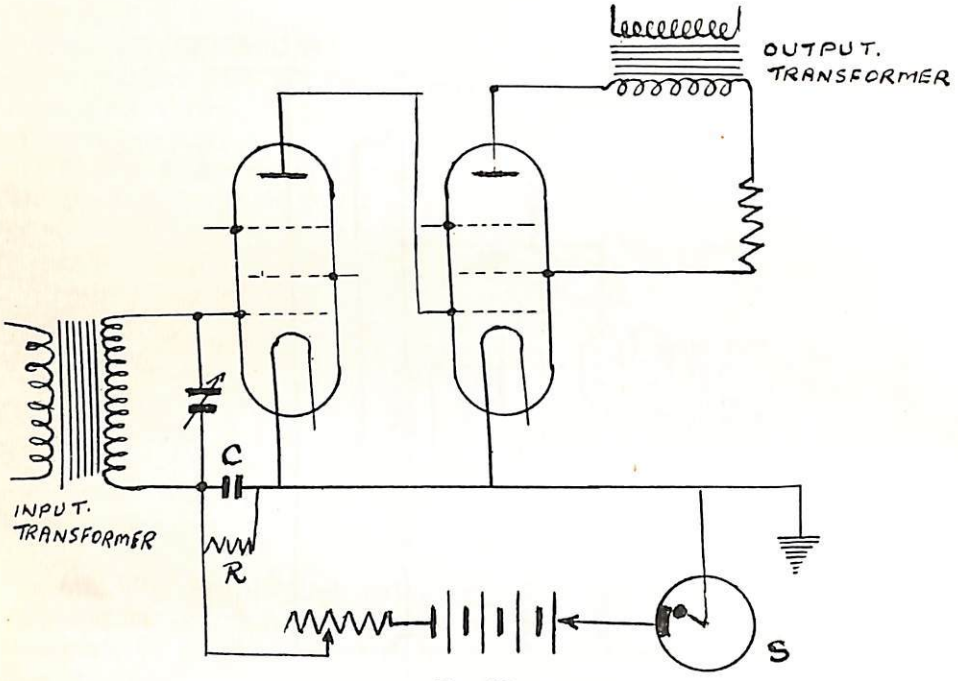


FIG. 60.

67. The gas-filled triodes of the Sperry compass.—Fig. 61. In a gas-filled valve (see § 54) when the gas is ionised the cathode and anode are, so to speak, short circuited and no matter what we do with the grid

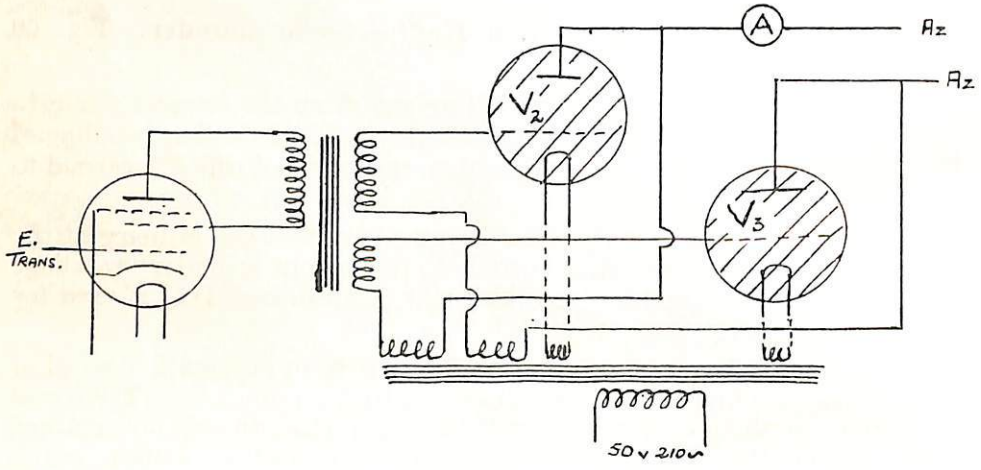


FIG. 61.

voltage current will continue to pass, so long as the anode is positive to the cathode. The grid starts the flow but once it is started the grid loses control and cannot stop it.

Now the two gas-filled triodes of the Sperry compass have A.C. applied to both grids and anode, this A.C. being supplied by the power transformer. The A.C. in the grid circuit is out of phase with the A.C. in the anode circuit. Now the valve can only strike if both grid and anode are positive together. [Assuming for simplicity that zero voltage is cut off point] but with this arrangement when one is positive the other is negative.

Further, the A.C. voltages in the two valves are of opposite phase (see Fig. 62). The signal current from the E transformer, having been amplified by the pentode valve, is fed to the grids of the gas-filled valves V_2 and V_3. We have already seen that if the phantom ring and vertical ring are not in line there will be a signal current of one phase if the phantom is off to one side and of the opposite phase if the phantom is to the other side. It follows then that the signal voltage will be in phase with the voltage on one grid and out of phase with the other.

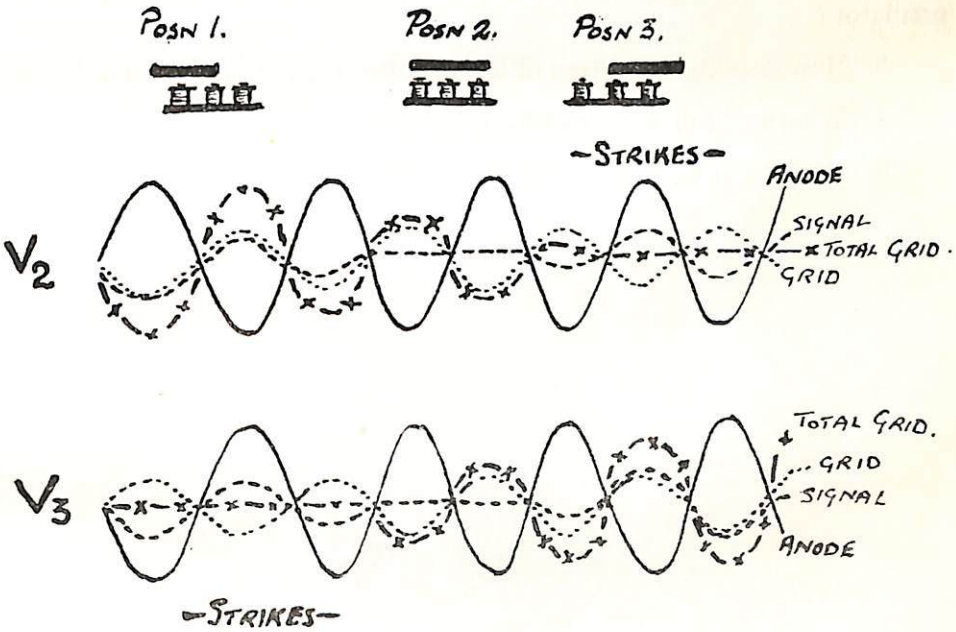


Fig 62.

Thus the total voltage on the grid of one valve will be increased and on the other valve will be decreased. When the grid bias becomes sufficiently small one valve will strike and will pass current to the azimuth motor causing it to run ahead or astern as the case may be.

Suppose at the beginning of Fig. 62 the phantom is to the East as shown on the top line. The signal will be in phase with the grid voltage of

V_2 and increase it as shown on the second line. The same signal will be out of phase with the grid voltage of V_3, where the total voltage will fall to zero. V_3 will now strike and pass current to the azimuth. As the azimuth motor turns ahead it will drive the phantom back into line with the vertical ring, the signal voltage will fall away (position 2, Fig. 62) and since both valves now have negative bias whenever their anodes are positive then neither valve will light. The momentum acquired by the phantom will however carry it over to the West side (position 3, Fig. 62). A signal of opposite phase is now produced and this wipes out the negative bias of V_2, enabling that valve to strike and running the azimuth motor astern. The process then repeats.

EXERCISE VII.

1. Describe a diode valve and say for what purposes it is used.

2. What is a triode valve ? How is it used as (*a*) amplifier (*b*) an oscillator ?

3. How does the operation of a soft valve differ from a hard valve ?

4. What is " full wave rectification " ?

5. Describe the construction of an indirectly-heated cathode.

CHAPTER VIII.

THE ECHO SOUNDER

68. The Echo.—Everybody is familiar with an echo by which a sound wave is reflected and returns along its original path. In an echo sounder a sound wave is sent through the water, is reflected from the sea bed, and the echo picked up. The speed of sound is affected very slightly by pressure, temperature, and salinity of the water, but the variations are too small to be of navigational importance except in hydrographic survey work or in the Red Sea or Baltic. A mean value of 4800 feet (800 fathoms) can be accepted as the speed of sound in water. If the echo takes half a second to get there and back it must have travelled 400 fathoms in all, 200 there, 200 back, and so the water is 200 fathoms deep.

Notice two important points :—

1. The instant of transmission must be accurately timed as well as the instant of return of the echo.

2. The sound made must be of brief duration. The essentials of an echo sounder are therefore :—

(1) Some means of sending the signal exactly on time.

(2) Some means of receiving the echo.

(3) An accurate timing device.

(4) A display to show the answer.

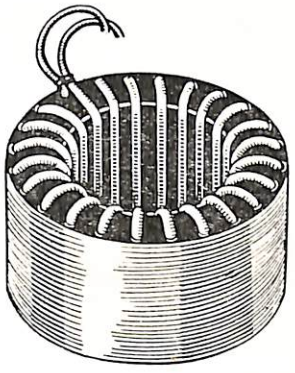


FIG. 63.—Pack-type Oscillator.

69. The signal.—The signal is a compression wave of fairly high frequency (15,000 c.p.s.) which is usually called supersonic but can be heard by most people. This vibration is produced by magneto-striction effects in the transmitter oscillator. Some metals, nickel in particular, expand and contract when subjected to a varying magnetic field (see "Munro's Electricity and the Magnetic Compass). The pack type

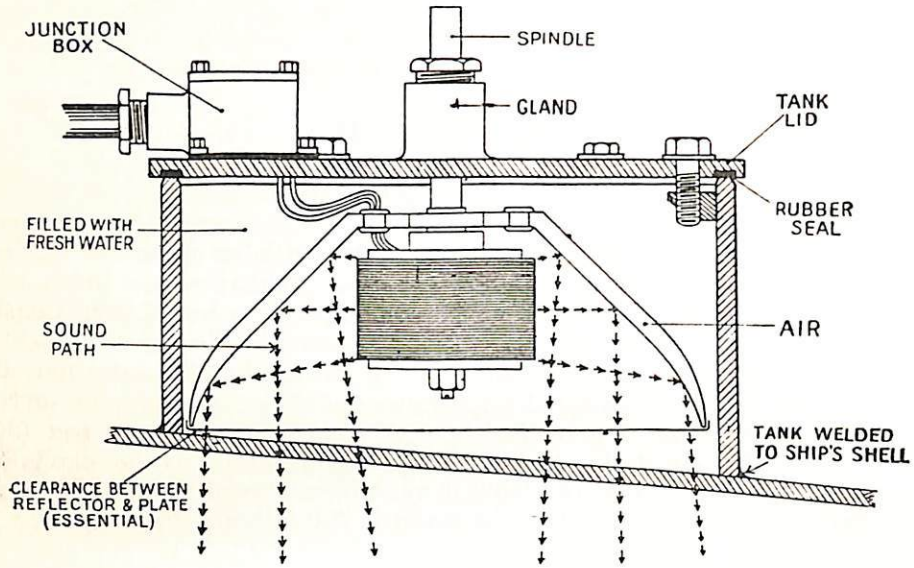

JUNCTION BOX
SPINDLE
GLAND
TANK LID
RUBBER SEAL
FILLED WITH FRESH WATER
SOUND PATH
AIR
TANK WELDED TO SHIP'S SHELL
CLEARANCE BETWEEN REFLECTOR & PLATE (ESSENTIAL)

FIG. 64.

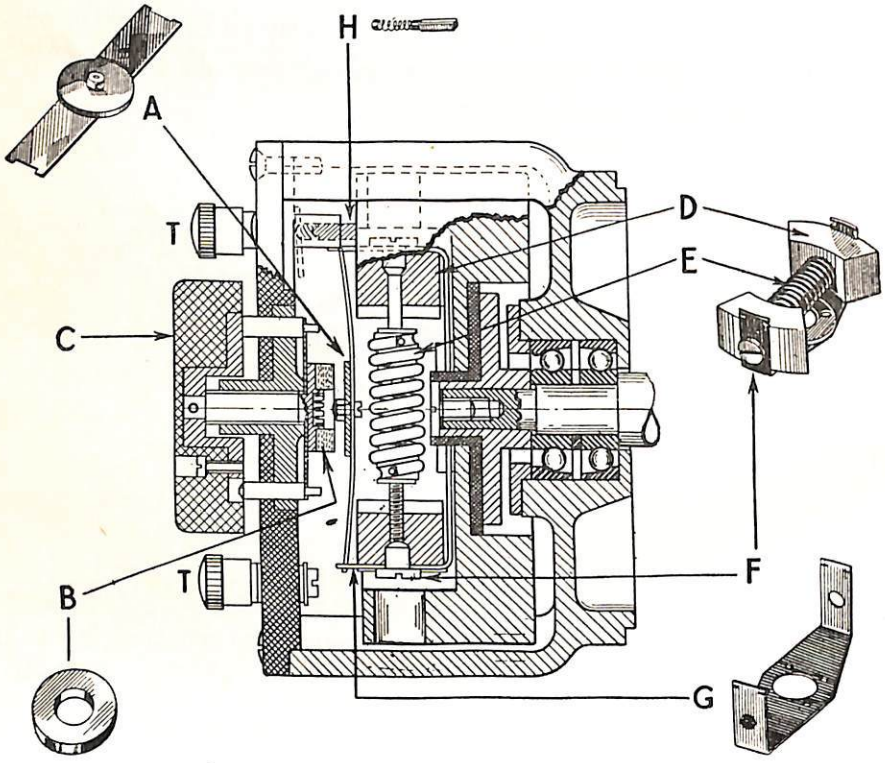

H
A
T
D
E
C
T
F
B
G

FIG. 65.

oscillator consists of a number of nickel stampings wound with a few turns of heavy wire. If a high-voltage A.C. current is passed round this torroidal winding it causes the nickel stampings to expand and contract alternately across their diameter. This sets up a compression wave (a sound wave) which is reflected by the parabolic reflection and concentrated into a beam of about 40°. This value is chosen to allow for rolling whilst still keeping the energy fairly well concentrated.

Note that it is the air in the reflector, not the metal, which acts as the reflector. The magnetic striction waves will travel quite readily through steel, so it is not necessary to cut holes in the hull (except in wooden vessels).

A high voltage—at least 400 volts—is necessary in the oscillator windings. There are various means of producing this A.C. current from the ship's D.C. supply.

70. The motor.—The driving mechanism of the sounder is a shunt field D.C. motor whose speed is carefully controlled by a governor.

To simplify discussion we have chosen the Kelvin Hughes Echo Sounder, M.S. 21 A as a typical type. In this case the motor is regulated to 2800 revs. per minute.

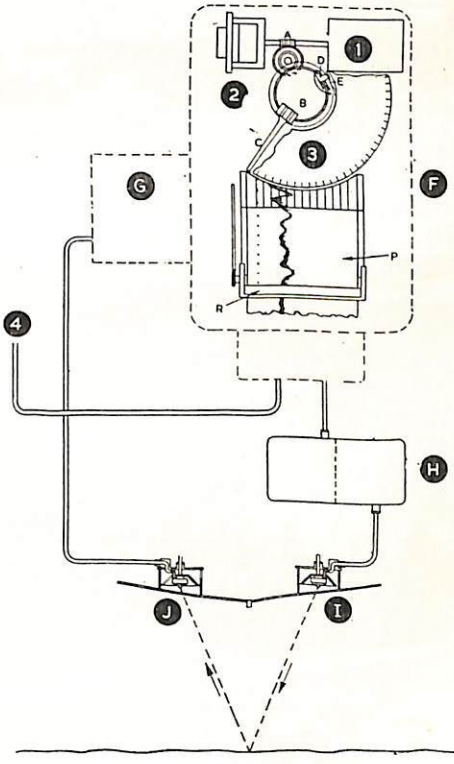


FIG. 66.

F. Recorder.
G. Amplifier.
H. Transmission Unit.
I. Transmitter Oscillator.
J. Receiver Oscillator.

1. Motor.
2. Governor.
3. Scale.
4. Ship's power supply.

A and B are contact points. B is a carbon ring mounted so that it can be adjusted by the knob C. This adjusting knob C is fitted with a clicking device, one click adjusts the speed by 5 or 10 revolutions per minute.

A resistance is connected across A and B When the motor is stopped the two arms of the spring G are bent inwards by the tension of the spring E. This bends A towards E and separates the contacts A and B. As the motor gathers speed centrifugal force on the two weights D overcomes the spring E and straightens out the flat strip on which A is fixed. This

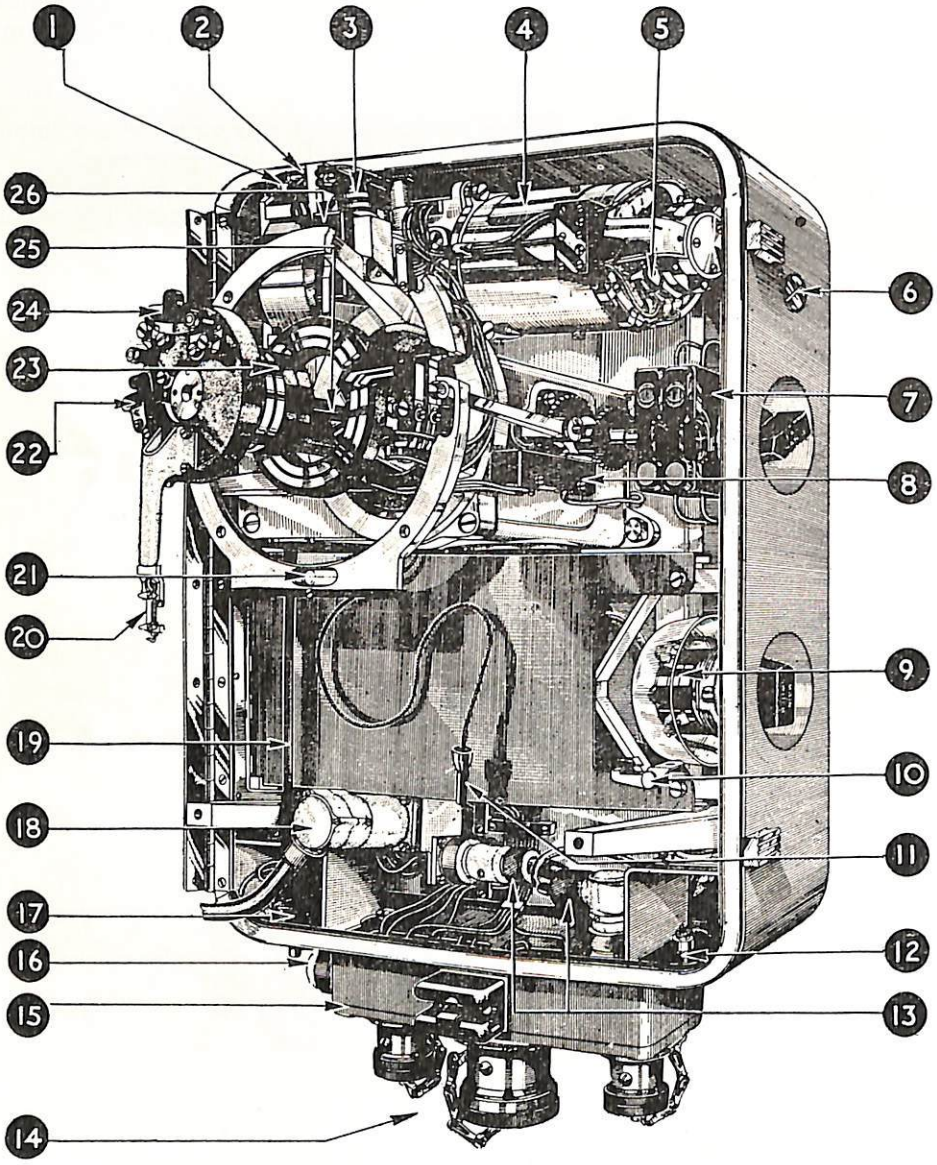


FIG. 67.

enables A and B to contact and the resistance is, more or less, short circuited. As the resistance is reduced the field current is increased and the motor speed is reduced (see " Munro's Electricity and the Magnetic Compass.")

71. Timing the transmission.—The control motor drives a drum fitted with a number of transmission switches (see Fig. 66). Through gearing the drum has two speeds, one for fathoms, and the other, six times as fast, for feet. At the correct instant a depression on the cam ring (7, Fig. 67) operates a brush fitted in a rocker arm to make contact and close the circuit to transmit the signal. This arrangement is similar to a contact breaker on the ignition system of a petrol engine (see " Munro's Electricity and the Magnetic Compass").

At the instant the signal is sent out the recorder arm must be at zero on the scale.

72. The converter unit.—This is the unit which produces A.C. from the ship's D.C. supply. In this case the D.C. supply is broken up into short pulses by a non-synchronous vibrator. The principle of the vibrator is almost identical with the " make and break " of the induction coil (see " Munro's Electricity and the Magnetic Compass").

The broken-up D.C. is fed to the primary windings of a transformer, the secondary windings of which are tapped to give the necessary A.C. voltages including a supply at 450 volts.

(See Fig. 67).

1.
2. Governor brush.
3. Field resistance.
4. Motor.
5. Brush-gear.
6. Detachable plug to allow access to motor fixing bolt.
7. Fuses.
8. Transmission selector switch, S.12.
9. Main switch, S.13.
10. Locking catch.
11. Low tension A.C. connector.
12. Socket for electric pencil.
13. Amplifier cable connectors.
14. "Niphan" waterproof cable connectors.
15. Junction box.
16. Tachometer cable socket.
17. Zero intensifier push-button.
18. Power pack cable connector.
19. Paper drive shaft.
20. Detachable stylus.
21. Indicator lamp.
22. Transmission switch, S.1.
23. Stylus drum.
24. Transmission switch, S.2.
25. Main shaft.
26. Initial suppression cut-out switch, S.10.

73. The transmitting relay.—In this model the transmitting relay is an electron device, a tetrode cold cathode gas-filled valve. This valve has a cathode (not heated) and an anode, and two grids. The grids are close together and if the potential between them is sufficiently high the gas in the valve will ionise (the valve is said to have triggered). This ionisation rapidly spreads until it covers the space between the cathode and anode, and the valve can then conduct.

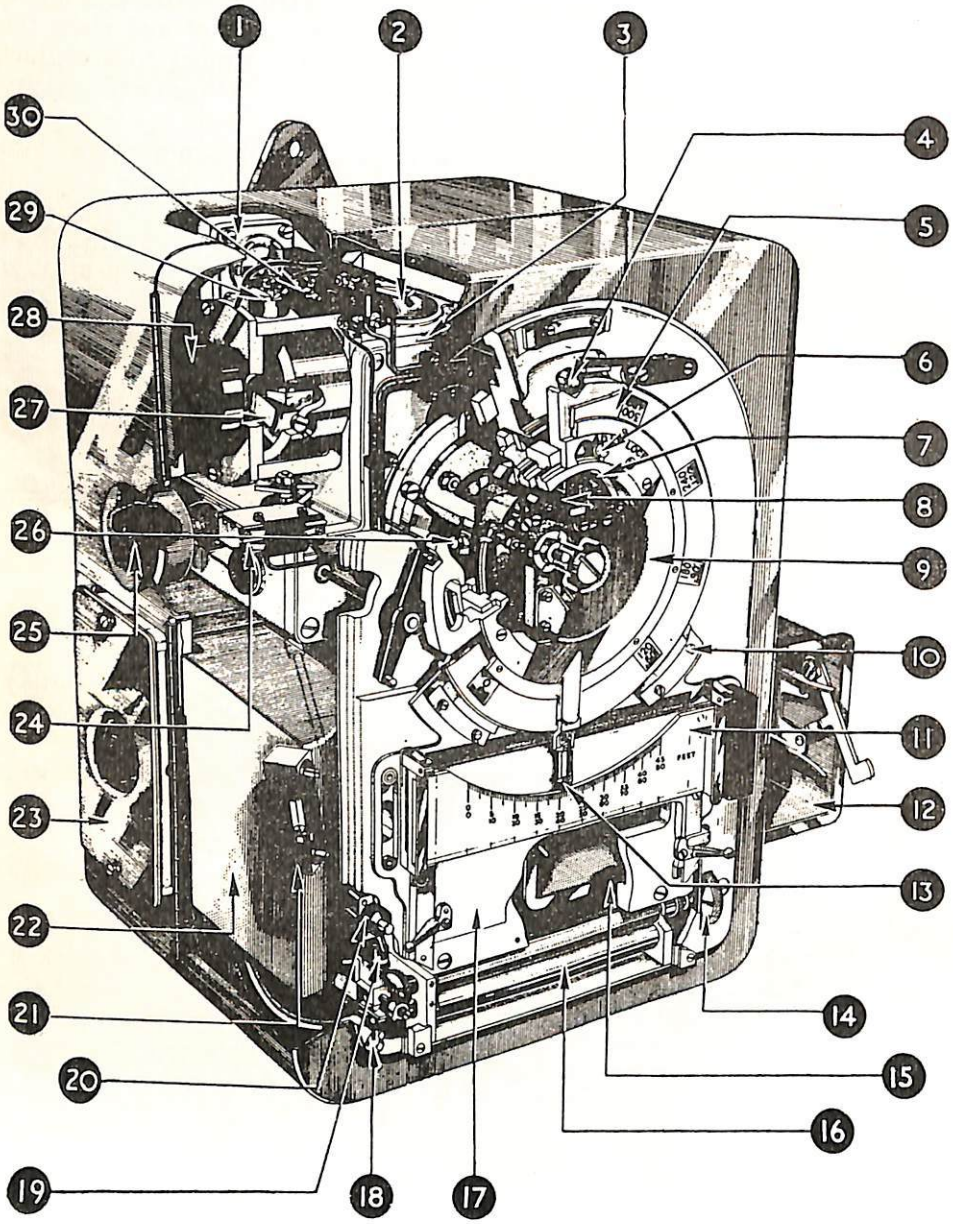


FIG. 68.

The partial circuit shows the vibrator which energises the primary of transformer T.2. Two steps of the secondary windings are shown. The lower winding is rectified through the selenium rectifier M.R.2 and this current passing through a high resistance charges the condenser C.17. The contacts X represent the transmission contacts (§ 63). For the most part of the rotation of the drum these contacts are open, when they close condenser C.17 discharges through the primary of T.1. The voltage generated in the secondary of T.1 triggers the grids of the valve.

During this time the secondary of T.1 rectified through the selenium rectifier M.R.1 is charging the condenser C.1 to its maximum capacity. As soon as the valve conducts C.1 discharges through the valve and through the transmitter oscillator.

In a few micros-econds the stored up energy of C.1 is expended in the oscillator. This electronic device switches on the high voltage without any danger of sparking on contacts. In some models a mechanical switch is used.

(See Fig. 68).

1. Anti-vibration rubber mountings.
2. Inspection cover.
3. Gearbox (forming main framework of assembly).
4. Check device for positive dial location.
5. "Perspex" dial.
6. Zero adjusters.
7. Cam rings.
8. Transmitting switches.
9. Detachable dust cover.
10. Stylus lifting ramp.
11. Fixed calibrated scale.
12. Paper container.
13. Recording stylus.
14. Thumb wheel for manual paper feeding.
15. Lower paper trough sealing spring.
16. Paper driving rollers.
17. Stainless steel writing surface.
18. Lever for disengaging paper drive.
19. Universal joint.
20. Scale lamp switch, S.7.
21. "Festoon" scale lamp.
22. A.C. power pack unit.
23. Amplifier unit slides out of case.
24. Enclosed interval marker switch, S.11.
25. Phase control rotates dial through 360°.
26. Stylus feed brush.
27. Constant speed governor.
28. Vernier speed control.
29. Tachometer brush.
30. Governor flywheel brush.

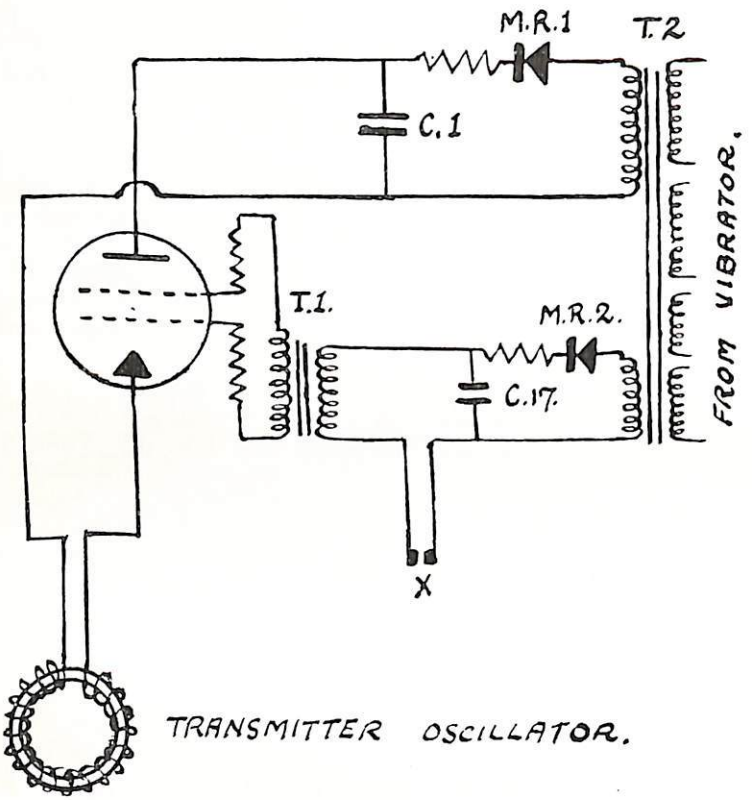


FIG. 69.

74. Receiving the echo.—The sound wave travels to the sea bed, is reflected and received by the receiver oscillator which is identical to the transmitter oscillator.

Providing there is some residual magnetism in the receiver oscillator when the compression wave falls on the nickel stampings of the oscillator it will produce an oscillating current. The magnetisation of the receiver oscillator is called " flashing the receiver " and if this is done on installation the residual magnetism lasts a long time.

The very weak oscillating signal is amplified and must be used to make the indication of depth. (See Chapter VII.)

75. Timing the interval.—An arm A is rotated anti-clockwise by the motor. It is exactly at X when the signal is transmitted and moves at a regular speed around the arc XY. When the signal returns it makes a current flow through the stylus, the paper beneath the stylus is slightly moist, and is impregnated with a solution of potassium iodide and starch. When a current passes from the stylus (cathode) through the paper to the

metal plate at the back (anode) it releases the iodine and causes a brown stain on the paper. (See "Munro's Electricity and the Magnetic Compass," § 36.)

The distance the arm has progressed accurately measures the time taken for the signal to return and consequently indicates the depth. The paper is slowly moved under the stylus by the paper drive mechanism and the brown marks thus build up into a continuous record of the depth.

The paper is kept in a hermetically sealed tank.

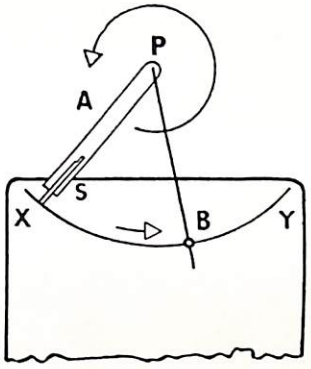


FIG. 70

In some echo sounders the recording unit consists of a rotating disc carrying a neon tube. The amplified echo lights the neon tube at a particular place during the revolution, depending on the depth. Retentivity of vision makes this appear as a steady light.

76. Errors.—A constant error will usually be obvious because the transmission zero line will be displaced towards the left or right and is due to incorrect adjustment of the transmitting switch.

A proportional error, being bigger with deep soundings is usually due to faulty motor speed. The speed can be counted either by counting the stylus revolutions or by listening to the clicks of the transmitter switch, the correct speed is engraved on the switch drum. An alternative method is to note the time interval between one row of interval dots and the next.

The sound waves are reflected from air bubbles and if there are bubbles (aeration) between the transmitting oscillator and the sea bed they may cause the signal to be scattered, and result in loss of echo. This is more likely when going astern or making a large alteration of course.

Straight lines or irregular marks are due to interference with the transmitter and double echoes are usually due to contactor interference. The first echo (shallowest depth) should be accepted.

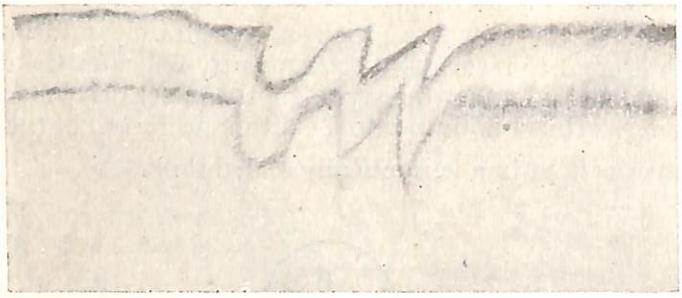


FIG. 71 (a).—Multiple echoes often occur in shallow water, always take shallowest depth.

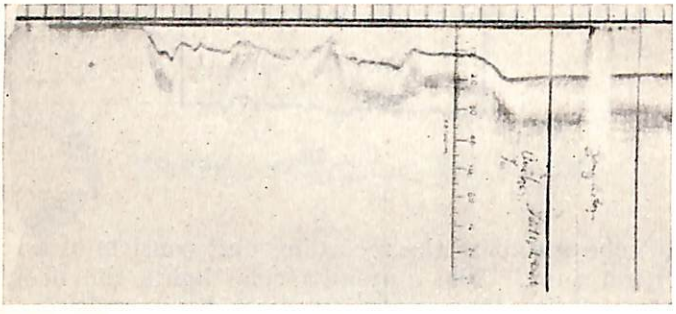


FIG. 71 (b).—Aeration produced by water turbulence, when turning or going astern will result in loss of echo.

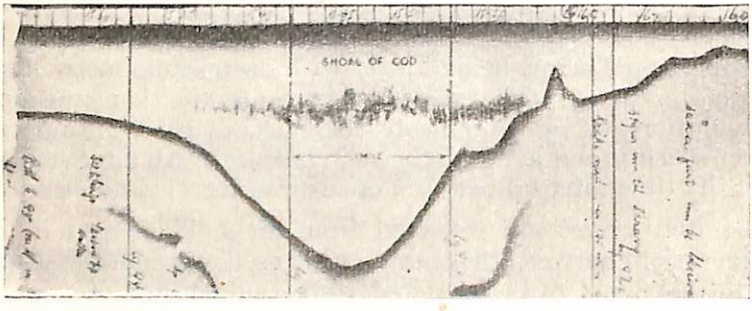


FIG. 71. (c).—A chart showing obstruction—usually a shoal of fish —between sounding apparatus and ocean floor.

FIG. 71 (d).—A spotted or confused record due to interference from motor commutator or faulty valve.

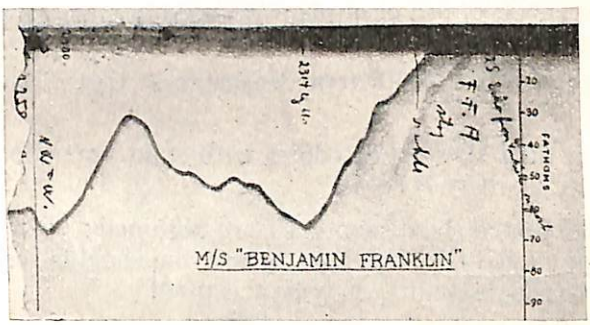


FIG. 71 (e).—"Cross noise" may make it impossible to distinguish echo in shallow water. Ususlly caused by imperfect initial suppressor operation.

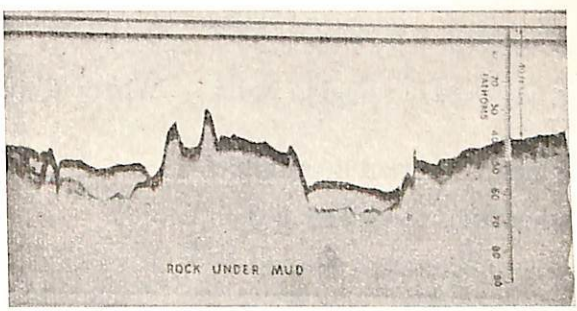


FIG. 71 (f).—Double or two-tone effect indicates soft mud on hard rock bottom.

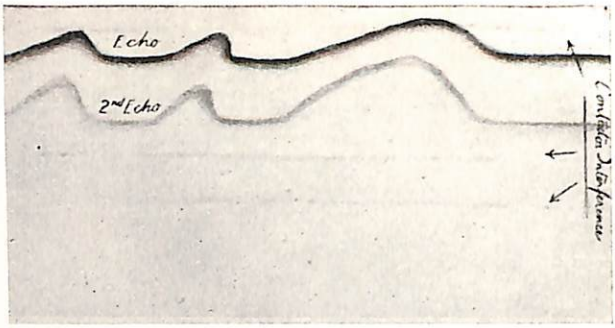


FIG. 71 (g).—Annoying lines due to contactor interference.

77. Admiralty Notices to Mariners, No. 967 of 1951, draws attention to the fact that false soundings may be due to :—

1. The returning echo being received after transmission interval has been completed once or perhaps twice. If maximum scale reading is 600 fathoms a reading of 50 fathoms may be 50, 650, or 1250 fathoms.

2. Dense shoals of fish or of plankton sometimes give an echo obscuring that from the bottom.

3. Layers of water of different density from that of the surrounding water.

4. Strong tidal streams or eddies with solid particles in suspension which may give feathery echoes.

When unexpected shoal soundings are obtained; then when charted depth does not exceed the scale reading and the shoal is seen to rise from the bottom, the shoal sounding may be accepted.

EXERCISE VIII.

1. Describe the principle of the echo sounder.

2. What is the speed of sound in water ? What effect has density on the speed of sound ?

3. Describe how the signal is transmitted.

4. Explain how the echo is received.

5. How is the time interval measured ?

6. What corrections must be applied to soundings by echo sounder ?

7. What effect has a wrong motor speed on the depths obtained ?

8. How does the stylus mark the paper ?

CHAPTER IX.

W/T DIRECTION FINDING

78. Propagation of electro-magnetic waves.—In "Munro's Electricity and the Magnetic Compass," §110, will be found a brief explanation of the propagation of electro-magnetic waves. These waves are not equally propagated in all directions. Some of the energy constitutes the ground wave (or direct wave) and follows, more or less, the curvature of the earth. Some of the radiated energy forms the sky wave (or indirect wave) and is emitted at varying angles.

79. The ground wave.—The front of the advancing wave is not vertical but is raked forward because the wave is travelling over a conducting surface.

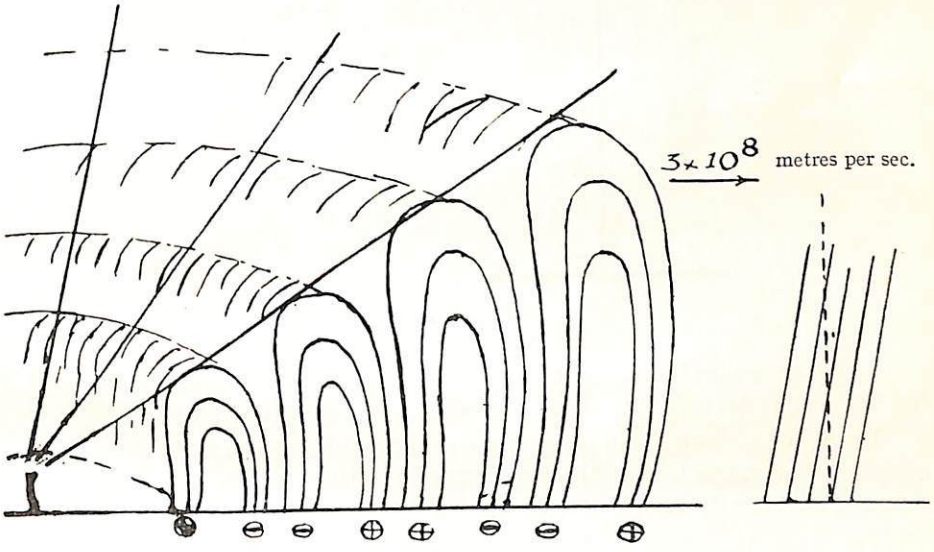


FIG. 72.

As the distance from the transmitter increases the ground wave grows weaker, its actual strength depending to a great extent on the nature of the surface over which it moves being very much better over sea than over land. Further, broadly speaking, the lower the frequency the longer the ground ray range. At high frequency the tilting of the ray results in a greater curvature than the earth's and the ray is soon lost.

80. The sky wave.—The sky wave would be quickly lost altogether if it were not for the fact that there exists some reflecting layers in the upper atmosphere which can reflect the ray back.

The outer atmosphere is considered to be divided into a number of layers with a rather indistinct and variable boundary between.

Very roughly up to 10 miles is the Troposphere.
From 10 miles to 25 miles is the Stratosphere.
From 25 miles to 50 miles is called the D region.
From 50 miles to 90 miles is called the E region.
From 90 miles to 250 miles is called the F region.

A reflecting layer probably consists of ionised gas. Ionisation may have been caused by the action of cosmic rays. In the D layer there is at least one reflecting layer the height of which is different by day from what it is by night. At a height of some 50 to 90 miles (in the E region) lies another reflecting layer called the Kenelly Heaviside layer (named after the two scientists who investigated it). The Kenelly Heaviside layer is possibly caused by ultra-violet radiation from the sun and its height varies between day and night. The lower limit moves upwards after sunset and falls again after sunrise. Changes also take place between summer and winter.

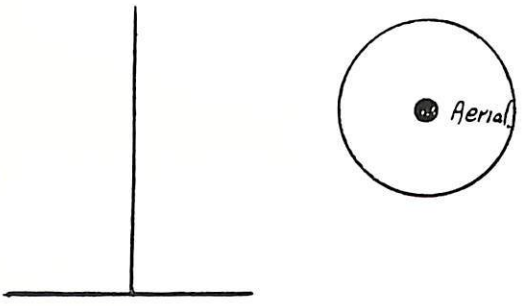


FIG. 73.

In the F region lies the third layer, the Appleton layer and it is possible that further reflecting layers lie at even greater heights than this.

Radio waves behave in many respects like light waves and are subject to reflection and refraction in the same way as light. When the reflected sky wave reaches the ground again the wave front may be very far from vertical.

81. Direction finding.—From what has already been said it is obvious that the wave front is very seldom vertical but for the time being let us assume that the front is truly vertical. Now suppose the travelling wave falls on a vertical aerial, the fluctuating positive and negative potentials which constitute the wave will generate an alternating current in the aerial which can be amplified and detected. Such an aerial will receive signals equally well from all directions, and if we plotted off the strength of signal received in each direction then the figure formed would be a circle. A figure like this is called a " polar diagram."

Suppose now that instead of a single vertical wire for an aerial we had used a loop.

If the loop is broadside on to the waves then both sides of the loop will be affected in the same way, Fig. 74 (a). The figure shows the negative part of the wave at the aerial, and, as is shown by the arrows, this will cause currents to flow upwards in each side of the loop, and since they are equal currents they will cancel out.

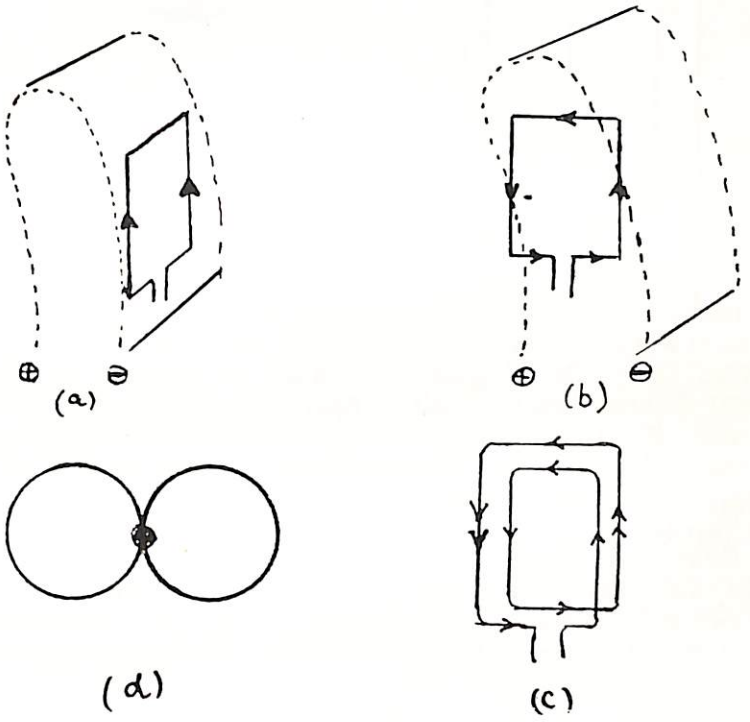


FIG. 74.

If, however, the loop is turned edge-on to the waves as shown in Fig. 74 (b) the current is downwards in one side and upwards in the other, and they are therefore cumulative. Fig. 74 (b) shows the loop to be as big as a half wave length, which is not likely to be the case, but even if the loop is small the result will be the same.

There will be no e.m.f. generated in the aerial when the loop is broadside on, but the e.m.f. generated will be maximum when the loop is edge-on.

This can be understood from another aspect for we may consider the magnetic part of the wave rather than the electric part. Normally the magnetic field is perpendicular to the electric field and both are perpendicular to the direction of movement of the wave, so that the magnetic field is horizontal.

Fig 75 shows a plan view looking down on the aerial loop and it is plain that in the edge-on position the loop will be cut by the maximum number of lines of force and so the e.m.f. generated will be a maximum.

A loop aerial, like this, will receive well when the loop is edge-on to the signal, but not at all when broadside-on. The polar diagram for a loop aerial is therefore shaped like a figure 8, Fig. 74 (d).

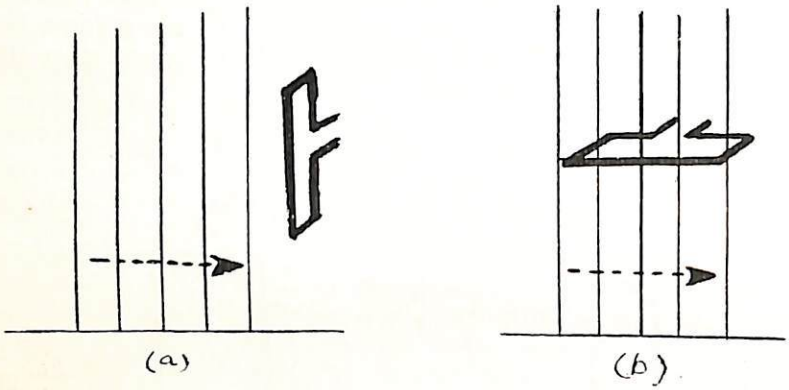


FIG. 75.

The loop constitutes a directional aerial and if it is rotated until the signal is nil it will then be broadside on to the direction in which the wave is travelling. The polar diagram shows that this position will be much more clearly defined than the position where the signals are a maximum.

One difficulty arises, however, and that is that there are two positions where the signal is minimum so we will be in doubt as to whether the sending station is in a certain direction or 180° away.

82. Sense.—Determining which of the two possible answers is correct is called " determining sense." If the loop is edge-on to the wave then the signal is maximum. If the loop is now rotated 180° although the signal is still maximum the current will now be flowing in the opposite direction around the loop (Fig. 74).

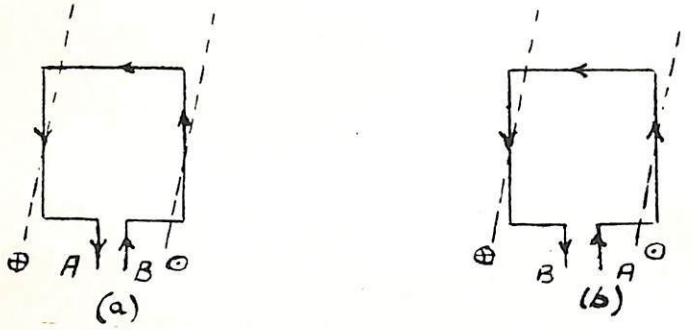


FIG. 76.

The aerial e.m.f. with the loop one way will be 180° out of phase with e.m.f. generated with the loop the opposite way. Now suppose we use a vertical aerial in conjunction with the loop we can imagine it to be in the middle of the loop—then the phase of the e.m.f. generated in this aerial will be in between the other two cases. That is, it will lead one by 90° and lag 90° on the other, Fig. 77 (a).

If now we can change the phase of the vertical aerial e.m.f. by 90° it will be in step with the loop aerial e.m.f. when the loop is one way. On the polar diagram this vertical aerial (sense aerial) will add to one half of

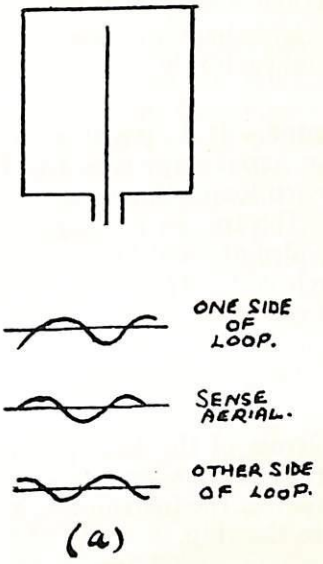


FIG. 77.

the figure. When the loop is rotated 180° the sense aerial will be 180° out of phase with the loop e.m.f. and will subtract from the other half of the figure eight polar diagram. The result will be a heart-shaped diagram (a cardioid) Fig. 77 (b).

Suppose the station was actually bearing N. Then with the sense aerial switched off we would find minimum signals with the aerial lying E. and W., and so we would know that the bearing was either N. or S.

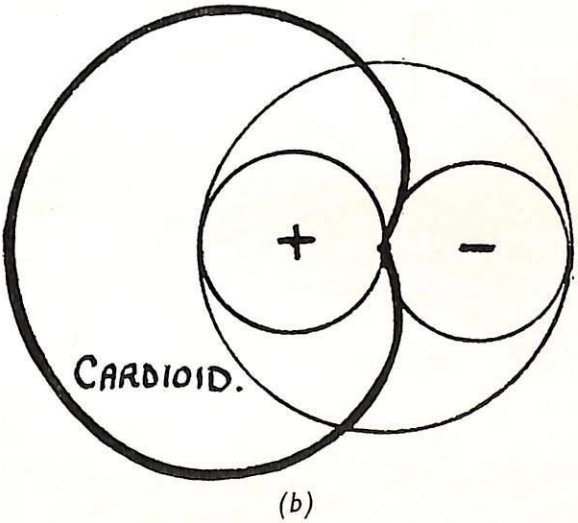


FIG. 77 (b).

With the sense aerial switched in, the minimum signal is obtained when the loop has been rotated 90° so that the edge A is North, and thus sense is determined. The whole job cannot be done with the sense aerial in because the cardioid has not a very well defined minimum. Indeed the minimum on the figure eight diagram is sometimes not very distinct and readings must be taken on each side.

83. The Goniometer.—It is possible to take a bearing without rotating the loop. If the aerial consists of two loops at right angles then the e.m.f. generated in each loop will depend upon the direction in which the waves are coming. The two aerial loops are connected to two coils inside the set which are also at right angles. In the centre of these is a rotatable coil—the search coil. The e.m.f. in the search coil will be a minimum when it lies in the same position relative to the goniometer coils as the wave does to the aerial coils. This system is called the Bellini-Tosi system and the search coil is a " goniometer " or angle measurer.

84. Errors.—The errors of the D/F system may be grouped as :—

1. Errors inherent in the wave.
2. Errors inherent in the instrument.
3. Errors due to the ship.

In the first group there are :—

(*a*) Night effect.
(*b*) Shore effect.
(*c*) Convergency.

85. Night effect.—The argument up to now has considered that the wave was travelling parallel to the earth, this is approximately true when the ground wave is observed but is not true when the sky wave is observed.

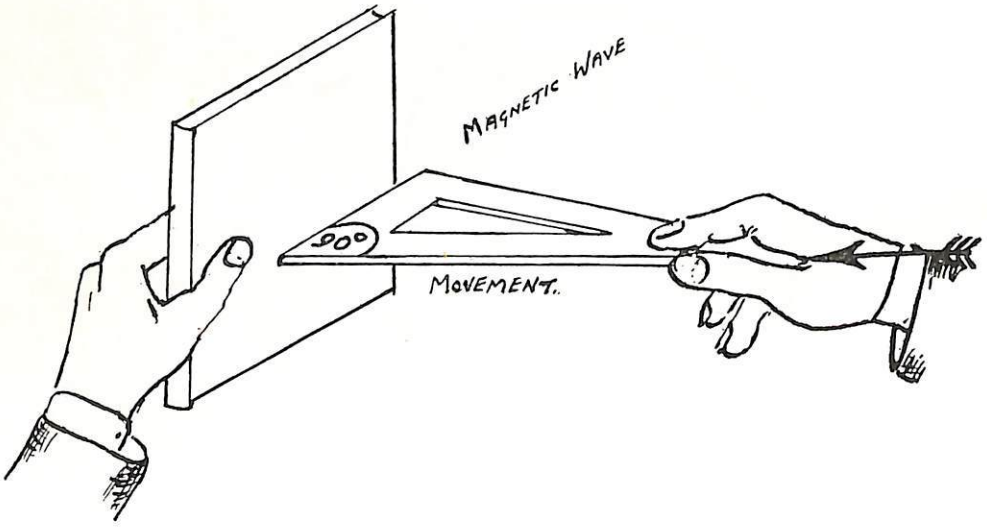


FIG. 78.

The electro-magnetic wave consists of the electric field, the magnetic field, and the movement all mutually at right angles.

Since this involves three dimensions it is difficult to represent in a diagram.

Hold a set-square in your right hand as shown in Fig. 78. One edge of the square represents the movement and must be maintained parallel to the movement of the square. The other edge of the square represents one line of the magnetic field. In the left hand hold a book to represent the aerial. Now the signal is minimum when the magnetic field strikes the aerial broadside on. In our illustrations the signal will be minimum when the edge of the set-square hits flat on the book.

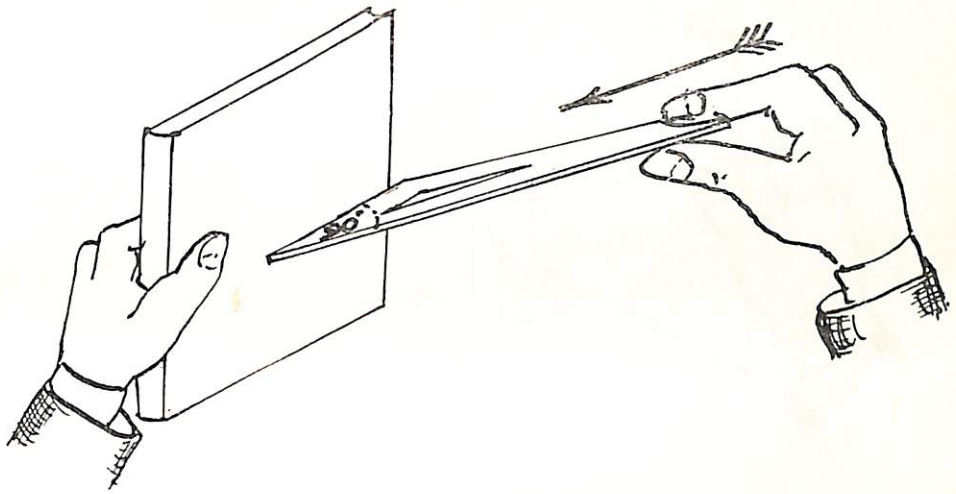


FIG. 79.

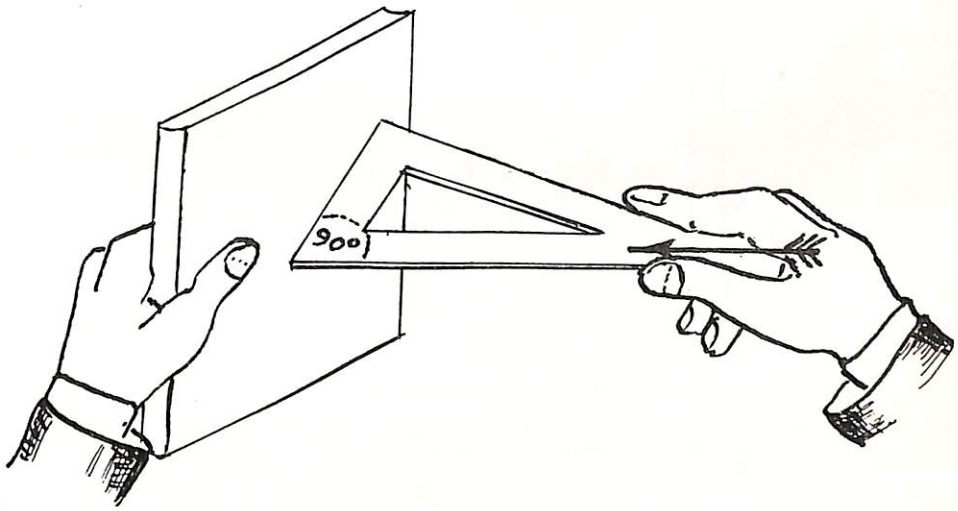


FIG. 80.

If the movement of the wave is horizontal, the magnetic wave edge of the set-square will hit flat on the book when the book is broadside on to the sending station.

If the movement is oblique and the magnetic wave edge horizontal the edge will again strike flat when the book is abeam to the direction in which the wave is travelling (Fig. 79).

Sometimes the magnetic wave is polarised, that is, it is rotated. If the wave is still travelling horizontally the book still indicates the direction (Fig. 80).

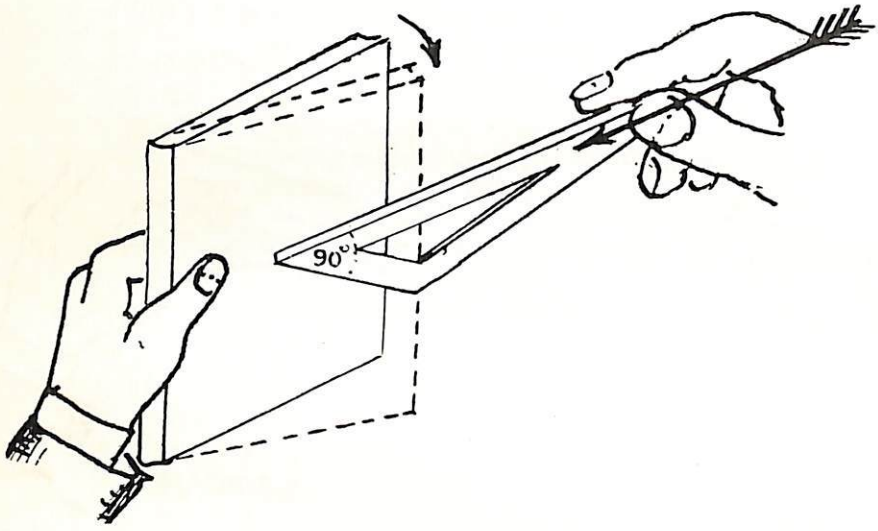


FIG. 81.

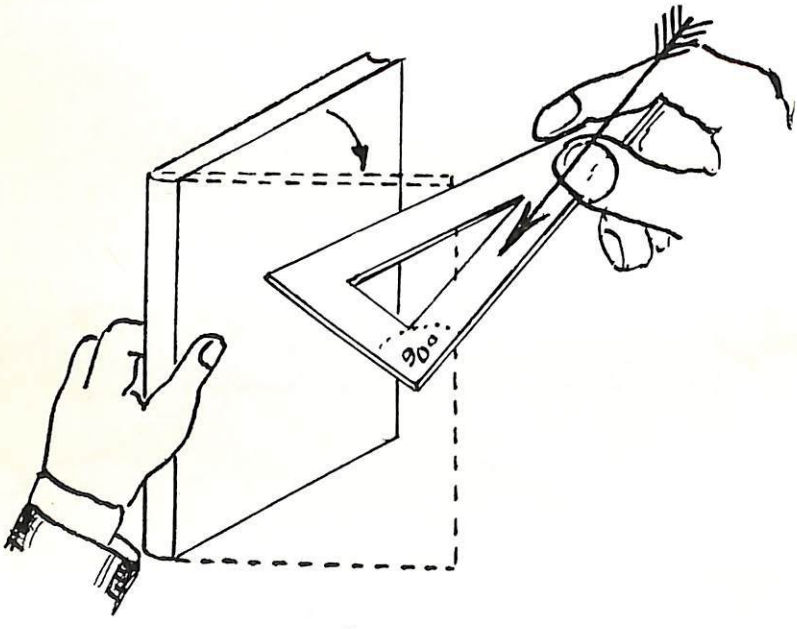


FIG. 82.

If the wave is travelling obliquely (remember to keep long edge of right angle parallel to the movement) and the magnetic wave (short edge of square) is *not* horizontal, then the book must be rotated before the square edge strikes flat (Fig. 81). Similarly in these circumstances the aerial will have to be rotated to get minimum signals. This error which arises with a polarised wave travelling obliquely is called night effect.

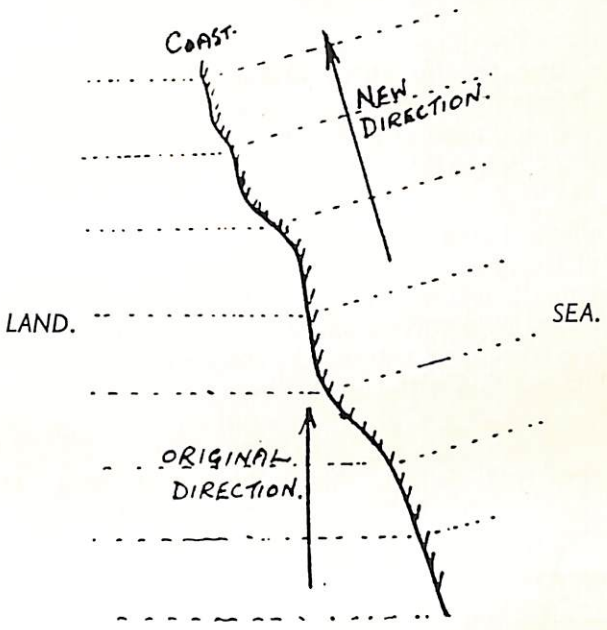


FIG. 83.

Note that if the magnetic wave is vertical and the wave travelling obliquely the error will be 90°. Since the wave is usually named from its electrical component, not the magnetic component, a wave like this is said to be horizontally polarised.

If the sky wave is much in evidence night effect must be suspected. On medium frequencies, by day, at ranges up to 100 miles night effect is not serious. The effect is at its worst within an hour either side of sunrise or sunset when the changes in the state of ionisation of the atmosphere are most violent.

86. Shore effect.—The velocity of wireless waves over the sea can be as much as 5% greater than over the land. If a wave crosses the coast line at an angle of less than 20° its direction of travel is appreciably changed.

The effect will be pronounced if high land intervenes between the ship and the station. Waves may sometimes be reflected from nearby high ground and the reflected wave may be polarised and so give appreciable errors.

87. Convergency.—The waves travel in a great circle and in order to find the mercatorial bearing of a station the half convergency correction must be applied. The correction is $= \frac{1}{2}$ d.long. Sine mean latitude and is always applied towards the equator. (See " Munro's Navigation.")

88. Instrument errors.—The errors inherent in the instrument are not our concern and will not be dealt with.

89. Errors due to the ship.—When the electro-magnetic wave strikes the ship it sets up alternating currents in the hull, rigging, aerials and any conductor, and each of these produces magnetic fields which link with and modify the magnetic field of the wave and so cause errors in the bearing.

The main effect is that of a loop in the fore and aft direction. To partly counteract this effect the fore and aft loop of the aerial (with B/T system) is often made smaller than the athwartship loop. Such a loop would not be affected by a wave coming from the beam. In the case of a wave coming from ahead, or astern, the loop would be affected but the resultant field does not link with the D/F loop aerial when it is in minimum position.

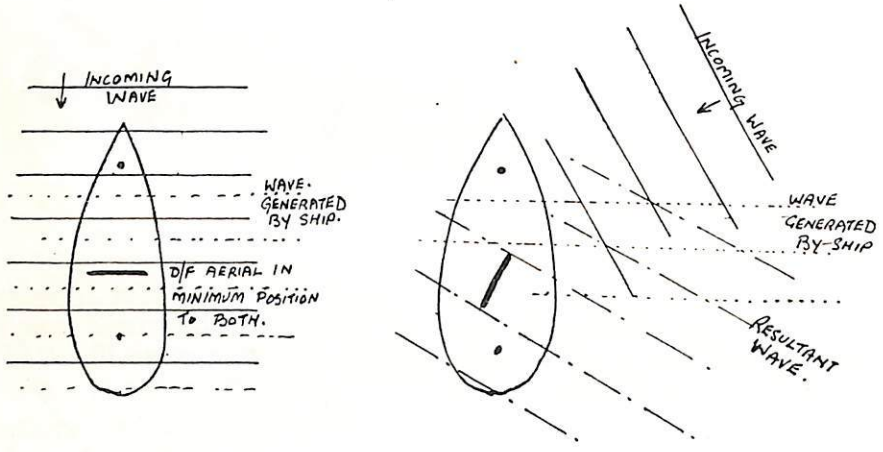


FIG. 84.

When the wave is on the quarter or on the bow the result of the ship effect is to make it appear as if the wave were coming from a direction nearer to the fore and aft line than is actually the case. This then gives rise to a quadrantal error which is usually graphed and can be applied to the bearings.

The vertical parts of the ship also give rise to errors of a semi-circular nature which have the effect of blurring the zero. A semi-circular corrector can sometimes be incorporated in the set to rectify this. Any unusual setting of this corrector should be taken as an indication of possible night effect.

CALIBRATED { Date _____ Off _____ By _____ Frequency 300 kc/s

CALIBRATION CURVE FOR DIRECTION FINDER

D/F { Type 5Y9 No _____ Choke _____

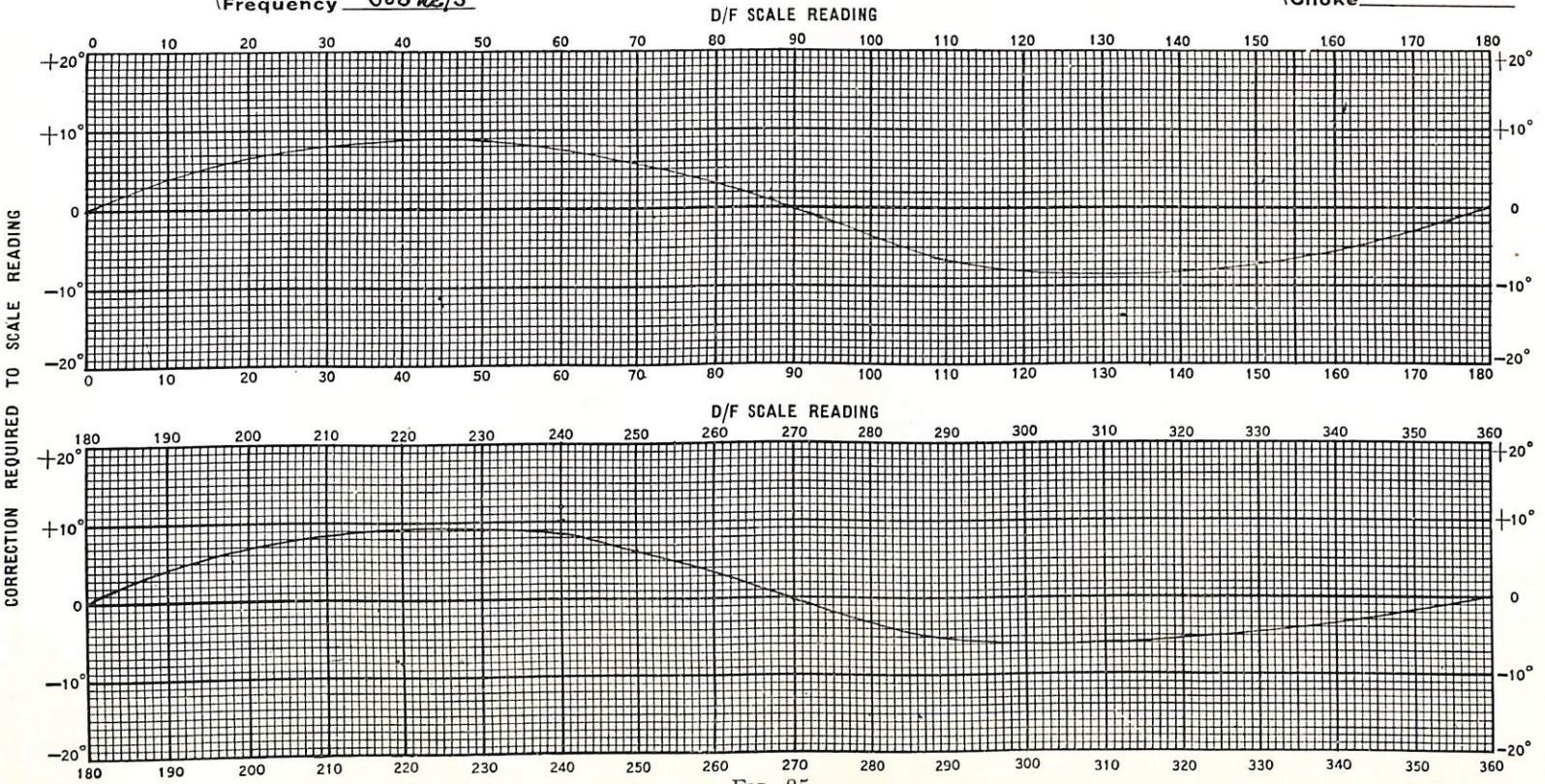


FIG. 85.

90. Calibration.—The errors of the D/F set are ascertained by observation and a curve of errors is drawn. It is essential that when the D/F set is calibrated everything should be in its sea-going position. The erection of broadcast aerials can cause serious errors in D/F bearings and it is essential that no near-by aerial is earthed.

EXERCISE IX.

1. Why must a D/F set be calibrated ? On what relative bearings are errors most likely ?

2. What is sense of a D/F bearing ? How is it determined ?

3. Are D/F bearings taken on maxima or mimima signal and why ?

4. What is the direction of a rotating loop aerial when taking the bearing of a station on the port beam ?

5. What is night effect ?

6. Describe land effect.

7. Why are insulators fitted on guys, etc., near a D/F loop aerial ?

8. What is the ionosphere and how does it affect electro-magnetic waves ?

9. How does the ship's hull affect relative bearings on an uncalibrated D/F ?

10. When is night effect greatest ?

CHAPTER X.

USING A D/F SET

91. Type 579.—The following instructions refer to the Marconi Type 579 set which is the type of set used by the Ministry of Transport for examination purposes.

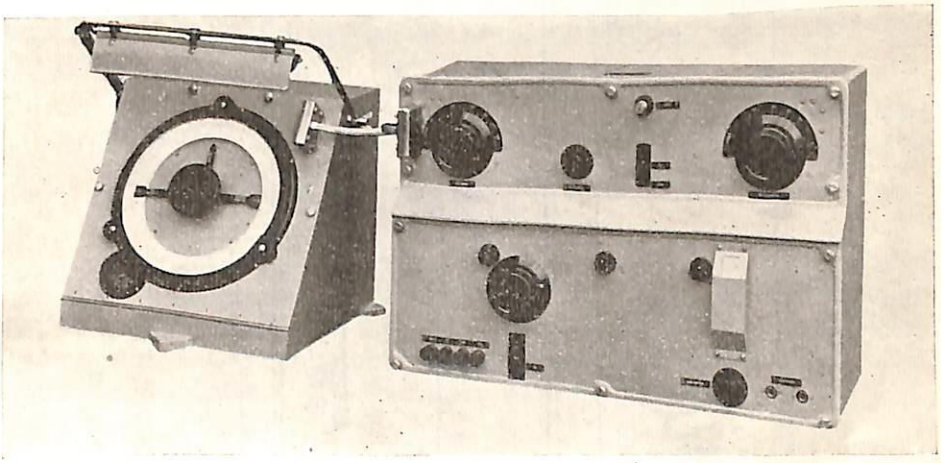


FIG. 86.

The set consists of aerial, goniometer, receiver, batteries. The aerial is of the B/T fixed loop type and sometimes incorporates a built-in sense aerial.

The goniometer has a main scale which gives relative bearings and a subsidiary gyro scale which will give true bearings.

The receiver has two assemblies in one case. The upper assembly embodies input, sense, and zero sharpening. The lower assembly is the amplifier.

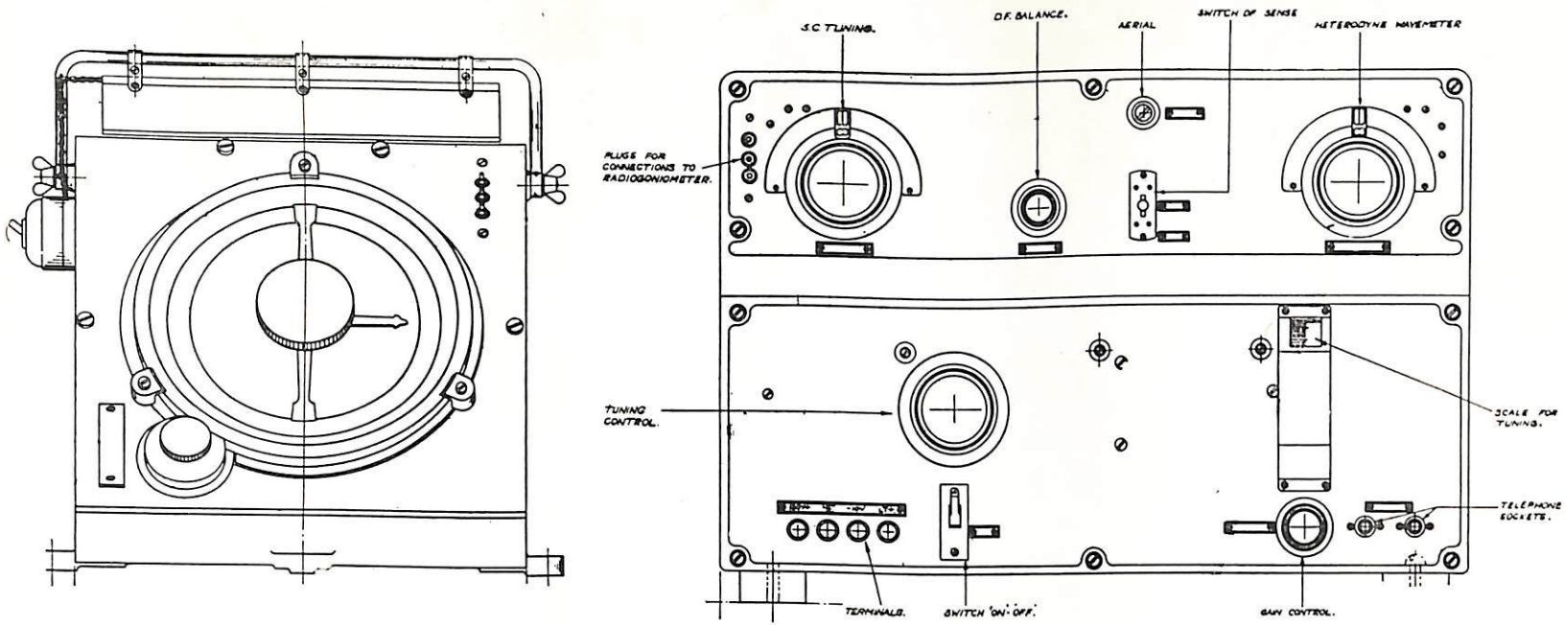
TO OPERATE :—

1. Isolate all aerials except the D/F aerials.

2. Switch on and tune in the required signal. If wave length of the wanted station is known

(*a*) Set wavemeter to the correct figure. Operate the other two controls until maximum noise level indicates that the circuits are in resonance.

(*b*) If required to receive continuous wave signals adjust wavemeter to produce the desired beat signals (see § 50) but if continuous wave signals are not required de-tune the wavemeter and this will cause practically all of the amplifier noise to disappear.



OUTLINE DRAWING OF D.F. RECEIVER TYPE 579

FIG. 87.

3. While searching for a station the goniometer should be rotated from time to time to ensure that it is not in the minimum position.

4. With the receiver tuned and the D/F balance set at zero rotate the goniometer once or twice and note that there are two positions 180° apart where the signal intensity is minimum. This is approximately the line of bearing.

5. Depress and hold down the sense switch. Rotate the stub sense pointer first to one and then to the other of the previously observed minima. Note which of the two gives the weaker signal and release the sense pointer.

6. Bring the relative bearing pointer round to this region. Re-adjust the S/C tuning condenser and, if necessary, reduce the gain control to enable the headphones to be worn closely over the ears.

7. The signal minimum will extend over a number of degrees, and it is now necessary to reduce this arc as small as possible. Hold the goniometer knob in the left hand and swing the bearing pointer back and forth through the signal minimum. Simultaneously, with the right hand, adjust the D/F balance until the minimum is an absolute zero.

8. The bearing should not be relied on if :—

(*a*) The zero is blurred. It should be perfect no matter how much gain is used.

(*b*) The zero moves.

(*c*) The station is over 50 miles away.

(*d*) There is possibility of coast refraction or shore effect from high land.

(*e*) The gyro or compass has not been checked.

If wavelength is not known set wavemeter to 1000, and, keeping other two controls in step, search for a signal. When signal is heard tune the wavemeter.

92. Correcting the bearing.—It sometimes happens that the zero cannot be reduced to a point but spreads over a band of a few degrees. In this case take a reading on either side, and accept the mid-way as the relative bearing.

The work should be set out thus :—

Example A.		*Example B.*	
Reading	043		002
	049		356
			360
Add	2)092		2)718
	046		359
Calibration error	+ 6	Calibration error	0
Relative bearing	052	Relative bearing	359
True course	+117	True course	+092
True G.C. bearing	169	True G.C. bearing	091
½ Convergency	+ ½°	½ Convergency	+ 1
Corrected Mercatorial bearing	169½	Corrected Mercatorial bearing	092

Note that if one bearing is on one side of N. and the other on the other side of N. then 360° should be added to the readings before dividing by 2.

The calibration error is obtained from the calibration curve. § 78.

ACCURACY OF BEARINGS.—For a 95% error of 3° (see § 100) shipborne D/F operating on 250-600 kcs. can generally be relied upon up to 300 miles range by day but only 25 miles range by night, providing other conditions are good.

There is a practical examination in the use of the D/F. for 1st Mate and Master.

CHAPTER XI.

SHORE-BASED STATIONS

93. Radio Direction Finding Stations (R.D/F.).—These are equipped to give a bearing of the ship. The ship must call up and request the service. The ship then transmits its call sign for a period of one minute during which time the station takes a bearing of the ship.

In some cases bearings are taken from three shore stations and the ship is then given a position.

Bearings can usually be depended upon to within 2° on the calibrated sector, but the signal may be affected by coast refraction, by night effect, when within an hour before sunset or an hour after sunrise, or when the distance by sea is over 100 miles.

Bearings will be given from the station and are designated :—

Class A when reliable within $\pm$ 2°
or if position is given when within 5 miles.
Class B when reliable within $\pm$ 5°
or if position is given when within 20 miles.
Class C when reliable within $\pm$ 10°
or if position is given when within 50 miles.

The signals are also designated Gonio A when the station is fitted with remote loops, and Gonio B when the station is fitted with weal loops.

Details of D/F stations, their frequencies, and calibrated arcs are given in Admiralty List of Wireless Signals, Vol. II.

94. Radio beacons.—These are stations which transmit signals so that ships can take bearings of them with D/F apparatus.

The frequencies of British radio beacons lie between 291·5 kcs. and 318·5 kcs. The corresponding wavelengths are between 1040 and 940 metres. Frequency is now universally used instead of wavelength. There is a conversion table in Vol. II. and

$$\text{Wave length in metres} = \frac{300{,}000}{\text{Frequency in kcs.}}$$

Some radio beacons transmit continuously and others only occasionally except during fog. Full details are given in Vol. II.

95. Synchronised signals.—Sometimes synchronization has been established between a radio beacon and an automatic sound signal (submarine or air) so that distance from the transmitter can be determined.

Wireless waves travel at 186,000 statute miles per second which is so fast that we can consider it instantaneous. The speed of sound in air is 1120 feet per second, that is ·18 mile per second, and sound in water is 4800 feet or 0·8 mile per second.

If a sound in air signal is transmitted at the same time as a wireless signal, the wireless signal will arrive first and the sound signal will be one second behind for every ·18 mile it has to travel.

To get distance from the transmitter we must carefully time the interval between the arrival of the wireless wave and the sound wave. This time interval must be multiplied by ·18 or 0·8 for air signals or submarine signals.

On Lœsø L.V. Denmark, there is a synchronised air signal. The air signal is sent as soon as the preliminary radio signal ends. The radio signal then consists of seven long dashes of 4·5 seconds with a pause of ·75 seconds (with a dot in the middle of the pause). Since sound in air travels one mile in $5\frac{1}{4}$ seconds the distance off can be counted by the radio signal.

At Texel there is a synchronised submarine signal. At the instant the submarine signal is sent the radio transmits a series of 15 one-second dash with $\frac{1}{4}$ second pause. Sound in water travels a mile in $1\frac{1}{4}$ seconds so once again the distance can be obtained by counting dashes until the submarine sound signal is received.

96. Talking Beacons.—A similar principle is used in the radio-telephony (R/T) talking beacons at Little Cumbrae and Cloch Point. The Cloch Point lighthouse transmits on the radio telephone :—" Cloch Point Light Houses speaking. At the instant when you hear through the air the commencement of the second blast of this fog signal, your distance in cables from this lighthouse is stated on the radio—one-two-three, etc."

97. Rotating Loops.—The best known example of these stations was the one at Orfordness, now discontinued. The scheme is designed to enable a ship to take a D/F bearing without any equipment beyond an ordinary radio receiver. The signal is transmitted by a directional aerial which rotates once per minute 6° per second. On passing North the station transmits the N starting signal (- - - —— - -) and on passing E. transmits the East starting signal (—— - - - - -).

The receiver times from the N starting signal until the received signal is a maximum. Six times the number of seconds elapsed will give the bearing of the ship from North. If the listener is nearly East from the station the N starting signal will not be clearly audible and in this case the observer must time from the East starting signal to the maximum signal. Six times the number of seconds will give the bearing of the ship from East.

EXERCISE XI.

1. What is the difference between a direction-finding station and a radio beacon ?

2. On what frequencies do British radio beacons operate ?

3. What is a synchronised signal ?

4. Explain the operation of talking beacons.

5. What is meant by a Class B bearing from a direction-finding station ?

CHAPTER XII.

HYPERBOLIC NAVIGATION

98. The Hyperbolic P.L.—It is much more difficult to measure a long distance accurately than a short one—it is obviously easier to measure a length of 6″ to the nearest $\frac{1}{10}$″ than to measure 6 miles with an accuracy of $\frac{1}{10}$″.

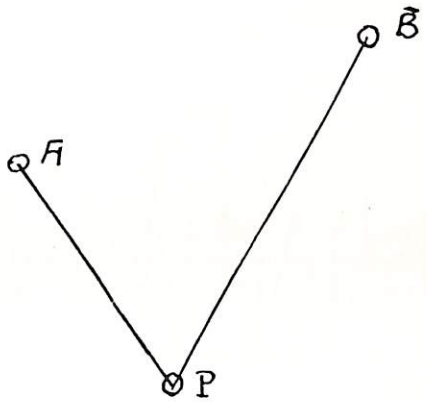


FIG. 88.

If A and B are two fixed points it is easier for a ship at P to measure accurately the difference PA ~ PB than to measure either PA or PB. Now if the difference PA ~ PB is known it fixes the ship on a curved position line.

In Fig. 89 A and B are 10 miles apart, the circles around A and B are each a mile apart.

The point P is 12 miles from A and 4 from B, PA ~ PB = 8.
The point Q is 11 miles from A and 3 from B, QA ~ QB = 8.
The point R is 10 miles from A and 2 from B, RA ~ RB = 8.

The line drawn through P, Q, R, S, etc., is a position line joining all the places where the difference between the two distances is 8 miles.

Had we taken a difference 7 miles we would have got the next dotted curve.

Each of these lines is a curve called a " hyperbola " and a full set constitutes a family of hyperbolæ.

If such curves are overprinted on an Admiralty chart the navigator could fix his position if he could determine that he is at the intersection of two curves.

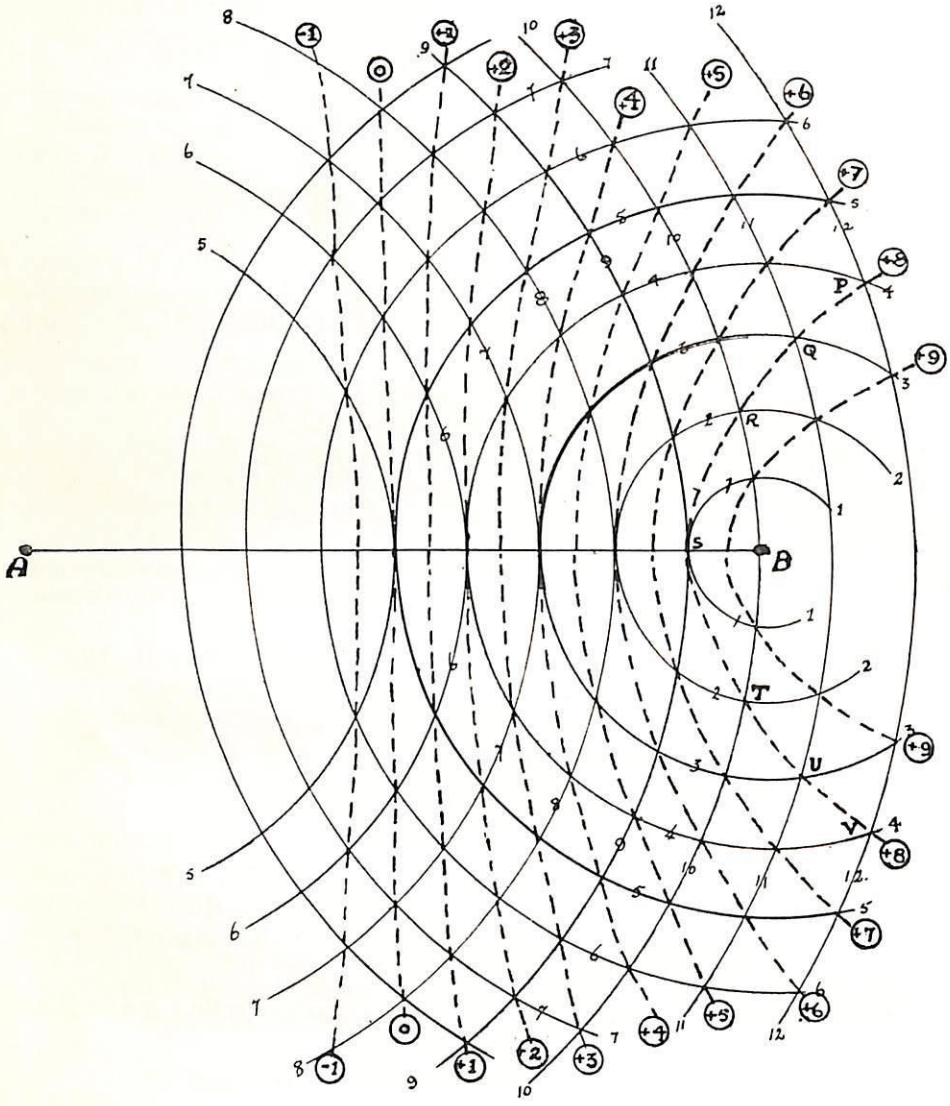


FIG. 89.

99. Determining P.L.'s.—If A and B are both sending out wireless signals the problem boils down to measuring the time interval between the receipt of the two signals. Since the speed of wireless waves is 186,000 miles per second the time interval will be extremely short and some special means will have to be found to measure it.

It is clear that A and B must not just transmit one little signal but must transmit a series of signals. Suppose A and B transmit signals at the rate of one a second. If the signal from B arrives $\frac{1}{10}$ second later than the signal from A it may mean that it has taken $\frac{1}{10}$ second longer or $1\frac{1}{10}$ seconds longer or $2\frac{1}{10}$ seconds longer because there will be no means of

distinguishing individual signals. It is probable then that some ambiguity will exist. The times involved will, of course, be only tiny fractions of seconds not as quoted here for convenience.

The signals transmitted may be either a series of short pulses as in Loran or an alternating signal as in Decca. In the latter case it will be necessary to measure the time interval between the wave peaks.

In the following Chapters we will discuss in more detail :—

Consol.—A system where the signals transmitted are C.W. (continuous wave) wireless signals sent out in such a way as to make a pattern of dots and dashes. No special equipment is necessary to use Consol beyond an ordinary ship's receiver and a chart, or a method of converting the signals to great circle bearings. Consol is a long range system suitable for ocean navigation but not for coastal navigation.

Decca.—The transmitted signals are received and compared by a special Decca receiver and the answer displayed by meters known as "decometers." Decca is a very accurate short range system requiring special equipment.

Loran.—An American system closely resembling the British GEE. It is a long range system suitable for ocean navigation and displays the information on a cathode ray tube. Special equipment is required.

100. Errors in hyperbolic position lines.—As in other cases, if the ship is known to be on two hyperbolic position lines at the same instant then she must be at the point where these cut. If the P.L. were exactly correct this would pin point the ship's position. Let us suppose however that both position lines may involve a small error.

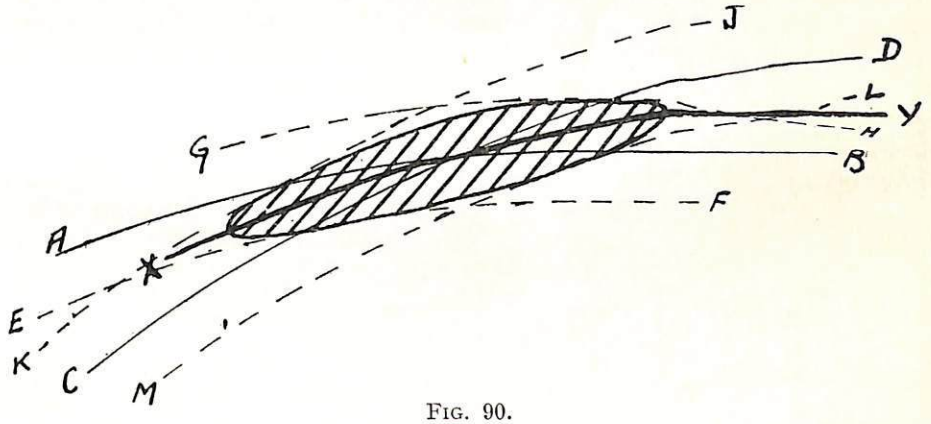


FIG. 90.

Suppose that AB is not an exact position line but is known to lie somewhere between GH and EF and similarly the position line CD is known to lie somewhere between JK and LM, then it is fairly obvious that the position of the ship is not accurately pin pointed. It would appear, however, that the position will be somewhere within the diamond.

In fact the chances are against both lines having maximum error the same way and closer calculation shows that the probable position of the ship is inside the elipse shown. This is called the elipse of error.

The reliability of the fix, it will be noted, may be much better in one direction than another. If yet another P.L. is available from some other source it should be crossed with the line XY bisecting the smaller angle between the hyperbolic position lines.

In considering errors it is usual to consider the 95% error, that is the error which will not be exceeded on 95% of the occasions concerned. Numerous observations will enable the 95% error to be found with considerable accuracy.

CHAPTER XIII.

CONSOL

101. Adding A.C. voltages.—We have already explained that alternating voltages are vector quantities to be added by the rules of geometry.

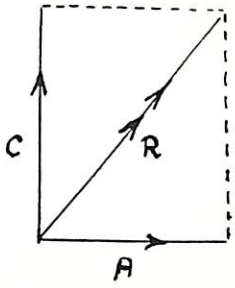


FIG. 91.

In Fig. 91 two alternating voltages are shown in a vector diagram. The voltage C is leading A by 90°.

The resultant is R (see also Chapter VI.).

102. The Consol pattern.—A Consol station transmits a C.W. signal, this is modulated, by signals transmitted by two subsidiary transmitters, in such a way that at some places a strong signal will be received for $\frac{3}{4}$ second and a weak signal for $\frac{1}{4}$ second ; which after detection will be heard as a series of dashes, and so that at other stations the $\frac{3}{4}$ second will be weak and the $\frac{1}{4}$ second strong, so giving a series of dots.

The subsidiary transmitting aerials are situated some 10 wavelengths from the master and their transmission is only about $\frac{1}{4}$ of the strength of the master. Let us for a moment, assume that the two slave transmitters are 90% out of phase with the master. A leading the master by 90° and C lagging on the master by 90°.

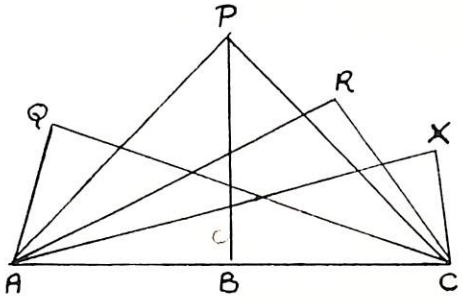


FIG. 92.

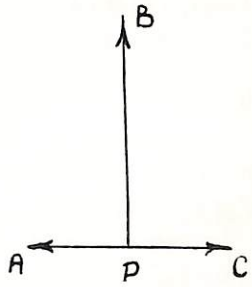


FIG. 93.

Let us consider a place P (Fig. 92) which is the same distance from A as from C. The signals from A and C leave in anti-phase, and since they have the same distance to travel to P they will arrive in anti-phase, as in Fig. 93, and will cancel each other out. There will be many such places as P not only where the distances PA and PC are exactly the same but also places where the difference between PA and PC is exactly a wavelength so that A and C signals are still received exactly out of phase.

Now consider a place like Q which is nearer to A than to C. The signal from A will not take so long to reach Q and will therefore be advanced (moved anti-clockwise). The signal from C will be retarded, since it has further to go.

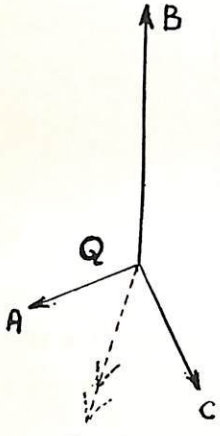


FIG. 94.

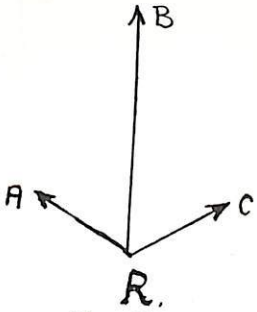


FIG. 95.

The resultant will be as shown dotted in Fig. 94 and will subtract from the master signal. The signal received will therefore be weaker than the signal from the master (B) alone.

At R (Fig. 92) which is nearer C and further from A. The C signal will be advanced (Fig. 95) and the A signal retarded. The resultant this time will be in the same direction as B and the received signal will be stronger than normal.

It will now be appreciated that the area is split up by a family of hyperbolæ joining all the places equidistant from A and C, all where the difference in distance is one wavelength, where difference is two wavelengths and so on. Since the base line is short these hyperbolæ will, at a little distance, be radiating lines embracing sectors of about 15°. Exactly on these lines A and C signals will cancel out, and the signal received will be that due to B, we will call these equi-signal lines.

In one sector all the places will be like Q receiving a weaker signal, whereas in the adjacent sector places will be like R receiving a stronger signal than usual.

Now this state of affairs lasts for $\frac{3}{4}$ second and then the signals from A and C are suddenly shifted in phase by 180°. This is called " keying " and the signals are keyed for $\frac{1}{4}$ second.

At places like P the signals, although reversed are still in anti-phase and cancel out.

Places like P still receive the equi-signal and will not notice any difference when keying takes place.

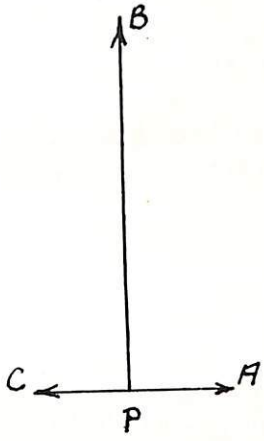


FIG. 96.

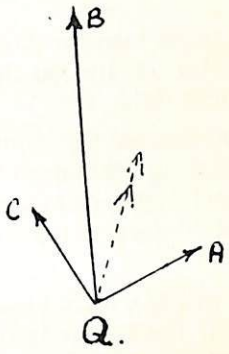


FIG. 97.

At places like Q (Fig. 97) the signals from A and C are reversed (compare Figs. 97 and 94) the resultant is now augmenting the B signal. For the quarter second that the signal is keyed Q will receive a stronger signal, and this will be heard as a series of dots.

At places like R (Fig. 98) keying will suddenly reduce the signal from a strong one to a weak one and R will hear a series of dashes.

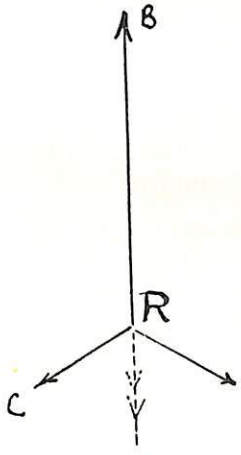


FIG. 98.

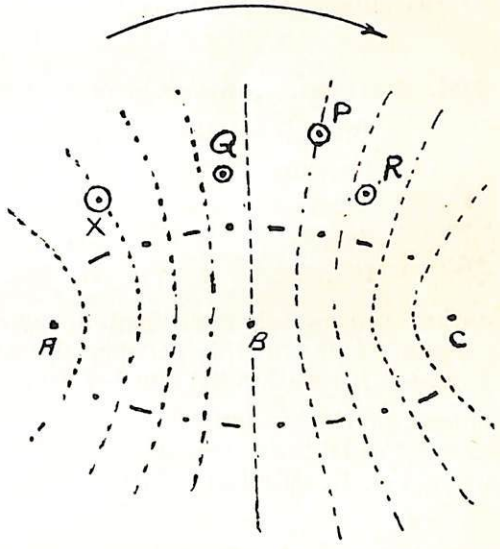


FIG. 99.

The pattern we see is really one of dot and dash sectors separated by equi-signal lines (Fig. 99).

These signals (in the case of Stavanger) are transmitted for a period of a minute but during the minute the whole pattern is rotated one sector. This is achieved by slowly advancing the phase of A and retarding the phase of B through 180° during the transmitting period.

Suppose Q (Fig. 99) was right in the middle of the dot sector at the beginning of the transmitting period, then as the pattern rotates Q will receive 30 dots and on the other side of the equi-signal will receive 30 dashes.

P will move into the dash sector and get 59 dashes. X will move into the dash sector too and get the same count, R will receive a few dashes and the remainder dots.

In practice as the equi-signal is approached the dots and dashes become indistinguishable so that some are missed. It has to be assumed that an equal number of dots and dashes were missed, so if a ship receives 20 dots and 36 dashes it is considered to be 22 dots and 38 dashes so as to total 60.

There will of course be a good number of position lines with a 22 dot count, but if the sector is in doubt it can be identified by an ordinary D/F bearing.

103. Receiving Consol signals.—Any set which will receive continuous wave signals will serve for Consol. Any ship's receiver will serve, and most broadcast receivers. A D/F set can be used but the aerial or goniometer should be as near to the maximum position as possible. If it is a considerable distance away from this setting appreciable errors may result. A receiver with automatic volume control (A.V.C.) must not be used unless the A.V.C. is disconnected.

104. Stations.—Stations at present operating are :—

Bushmills (MWN)	266 kcs.	= 1130 metres
Stavanger (LEC)	319 kcs.	= 940 metres
Lugo	303 kcs.	= 990 metres
Seville	311 kcs.	= 964 metres
Plonéis	257 kcs.	= 1171 metres

the station transmits its identification signal a 2-second break, the keying cycle described above (this occupies 1 minute in the case of Stavanger and ½ minute for Bushmills) another break and the identification signal.

Consol charts are published by the War Office and the Admiralty. Tables are available to convert Consol counts into great circle bearings and are in Vol. II. Admiralty List of Wireless Signals.

105. Reliability.—The range of Consol over the sea is about 1000 miles by day and 1200 miles by night. It is not sufficiently reliable to be used when closing danger. The accuracy becomes very poor on the extension of the base line. It is useless within 25 miles of the transmitter.

At distances around 200 miles there is the possibility of receiving both ground wave and sky wave when considerable error will result. Consol sometimes gives positions 12 miles in error off Flamborough Head which is about this critical range from Stavanger.

Consol is none the less a useful aid which is available to any ship without requiring special equipment. It is an ocean navigation aid only.

EXERCISE XIII.

1. What reliability would you place on a position obtained by Consol signals ?

2. Explain what is meant by an equi-signal ?

3. How is a Consol count taken ?

4. Where are Consol signals least reliable ?

5. What kind of receiving apparatus is used in conjunction with Consol ?

6. What is the coverage of a Consol station ?

CHAPTER XIV.

DECCA

106. Sending the signals.—Fig. 101 shows a master station with three slave stations disposed around it in approximately an equilateral triangle. All four stations are transmitting signals which are very carefully locked in phase, each station is at a different frequency so that the signals retain their individuality and are received by a special four-channel receiver. The receiver compares each signal with the master signal and records on a meter (a decometer) whether or not they are in phase. The equi-phase lines for each slave will form a family of hyperbolæ having as axis the base line between slave and master.

107. Frequencies.—The transmission frequencies are related to each other in a simple numerical way. We will express the frequencies in terms of "f per second" where f indicates units of 14·167 kilocycles per second. When we say that the master transmits at $6f$ we mean at $6 \times 14{\cdot}167$ kcs $= 85$ kcs.

The transmission frequencies are :—

Master	$6f$.
Red slave	$8f$.
Green slave	$9f$.
Purple slave	$5f$.

Wireless circuits are available to multiply or divide frequencies by simple numbers. When the master signal is received by the slave station it undergoes frequency multiplication and is re-transmitted exactly in phase with the master.

Let us consider only the Red slave, whose signals are at $8f$.

At the receiver this signal is multiplied by 3 to make it $24f$ and the master signal is multiplied by 4 to make it $24f$ too. Now that the signals are at the same frequency their phase can be compared by a phase meter.

108. The Decometer is a phase meter the dial of which is marked off to read $\frac{1}{100}$ part of a phase. Now we could draw lines on a chart (hyperbolæ) joining those places where the signal from the red slave will be exactly in phase with the master signal. The space between these lines is called a "lane," the decometer reads to an accuracy of $\frac{1}{100}$ of a lane.

Now both signals were exactly in phase when transmitted. If when received the slave signal is lagging 90° on the master signal, it means that the extra time it has taken on its journey has put it behind by $\frac{1}{4}$ wavelength

FIG. 101.

or $1\frac{1}{4}, 2\frac{1}{4}, 3\frac{1}{4}, \ldots$ wavelengths. Now the comparison frequency $24f$ is really a frequency of 340,000 cycles per second and so the additional time taken by the slave signal is $\frac{1}{4} \times \frac{1}{340{,}000}$ seconds or $1\frac{1}{4} \times \frac{1}{340{,}000}$ seconds, etc. Remembering that the waves are travelling 186,000 miles per second, then the extra distance via the slave is $\frac{186{,}000}{1{,}360{,}000}$ or $\frac{5 \times 186{,}000}{1{,}360{,}000}$ or $\frac{9 \times 186{,}000}{1{,}360{,}000}$ miles, that is ·137 m., ·685 m. or 1·233 m. This means we must be on one of a number of hyperbolic P.L.'s each of which is separated by a Decca "lane."

As can be seen from Fig. 101 the width of a "lane" increases as we get further away from the base line joining the stations.

The pointer of the decometer is geared to another pointer which (in the case of the red slave) makes one revolution in 24 lanes (the comparison frequency is $24f$). Each group of 24 lanes is called a zone and zones are lettered. The zone letter is indicated by another little dial which is changed every time the lane pointer makes a complete revolution.

As the ship moves over the Decca pattern the fractional pointer will record fractions of a lane, the lane pointer will keep count of whole lanes and the zone dial will indicate the zone.

If the setting of the instrument was correct at the beginning of the passage it will remain correct (excepting failures). If the ship just switches on the set in the middle of the pattern the fractional pointer will correctly indicate the fractional part of a lane but the other two will pick up from wherever they happened to be and will not show correctly. If the position of the ship is known they can be set to the correct Decca reference.

If, however, the position of the ship is in doubt then there will be very considerable ambiguity. This can be overcome by " lane identification " but before considering this let us look at the green and purple slaves.

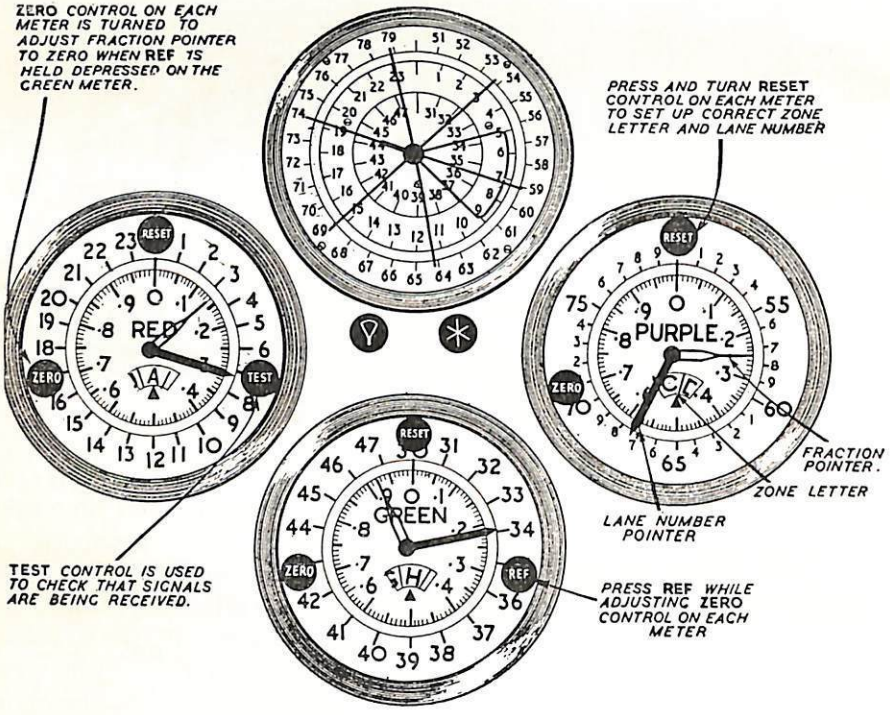

ZERO CONTROL ON EACH METER IS TURNED TO ADJUST FRACTION POINTER TO ZERO WHEN REF IS HELD DEPRESSED ON THE GREEN METER.
PRESS AND TURN RESET CONTROL ON EACH METER TO SET UP CORRECT ZONE LETTER AND LANE NUMBER
RESET
RED
ZERO
TEST
PURPLE
FRACTION POINTER.
ZONE LETTER
LANE NUMBER POINTER
GREEN
REF
TEST CONTROL IS USED TO CHECK THAT SIGNALS ARE BEING RECEIVED.
PRESS REF WHILE ADJUSTING ZERO CONTROL ON EACH METER

FIG. 102.

109. The Green slave transmits at a frequency of $9f$ so that the signal is received separately to that from the red slave. The green slave signal is multiplied by 2 to give $18f$ and the master signal is multiplied by 3 making it $18f$ also. Just as the red slave is compared at $24f$ the green slave is compared at $18f$. In this case there are 18 lanes in a zone. To avoid confusion the lanes are numbered from 30 to 48.

110. The Purple slave transmits at $5f$. The comparison frequency is $30f$ and the lanes are numbered 50 to 80.

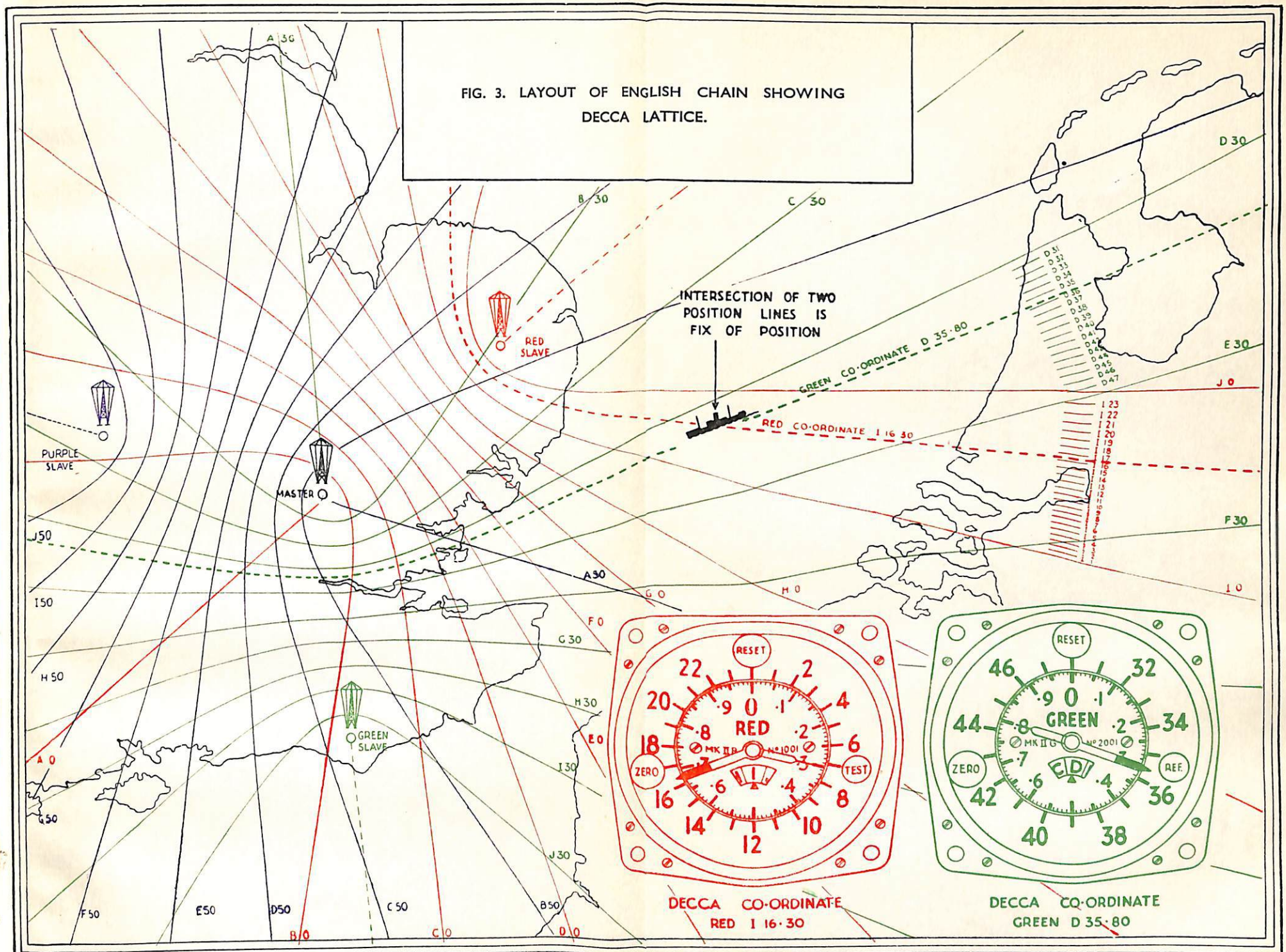


FIG. 3. LAYOUT OF ENGLISH CHAIN SHOWING DECCA LATTICE.
INTERSECTION OF TWO POSITION LINES IS FIX OF POSITION
GREEN CO-ORDINATE D 35·80
RED CO-ORDINATE I 16 30
RED SLAVE
PURPLE SLAVE
MASTER
GREEN SLAVE
A 30
B 30
C 30
D 30
E 30
F 30
G 30
H 30
I 30
J 30
A 0
B 0
C 0
D 0
E 0
F 0
G 0
H 0
I 0
J 0
A50
B50
C 50
D50
E50
F 50
G50
H 50
I 50
J50
RESET
RED
ZERO
TEST
MK IIB
No 1001
DECCA CO-ORDINATE
RED I 16·30
RESET
GREEN
ZERO
REF.
MK IIG
No 2001
DECCA CO-ORDINATE
GREEN D 35·80

111. The Fix.—Each slave has its own decometer giving a position with an accuracy of $\frac{1}{100}$ lane. As we get further away from a station the width of a lane increases, but the width of a lane on the base line (the narrowest part) is, in the case of the English chain :—

Red lattice	481 yards.
Green lattice	641 yards.
Purple lattice	385 yards.

The stations are so placed that at least two of the position lines will give a good cut.

112. Lane identification.—Once every minute the transmission of the stations is changed to bring another dial into the picture for the purpose of lane identification.

It will have been appreciated by now that the shorter the wave length the narrower the lanes will be, but also the greater the ambiguity. If we can compare on a long wave length much of the ambiguity will disappear.

The lane identification meter has two pointers, a vernier pointer with six arms, and a sector indicator (see Fig. 102).

This sector indicator is a phase meter comparing signals at a frequency of $1f$, and the vernier pointer is comparing signals at $6f$. The vernier pointer has six times the accuracy of the sector pointer but has also six times the ambiguity, but the sector indicator shows which of the six arms should be read and so removes the ambiguity.

The wide lane of the lane identification meter is equivalent to a zone on the ordinary comparison frequency.

During red slave identification the master transmits at $5f$ and $6f$ and the $1f$ necessary for comparison is obtained by subtracting these. The red slave transmits at $8f$ and $9f$ (the normal red and green frequencies) the difference again provides the necessary $1f$.

For the vernier comparison at $6f$ the master transmission at $6f$ is used and the red slaves signals at $8f$ and $9f$ are multiplied to their normal comparison frequencies of $24f$ and $18f$ the difference of which is again $6f$.

During green indentification the master transmits at $5f$ and $6f$, and the green slave at $8f$ and $9f$.

During purple identification the master is again transmitting at $5f$ and $6f$ and the purple slave changes to $8f$ and $9f$.

While one slave is transmitting the identification signal the other two slaves are dead. This state lasts for just over half a second and during this time the decometer pointers which are not energised are locked so that they cannot move.

Only one identification takes place at a time. The sequence of events is as follows :—

At say 08h. 00m. 00s. red identification begins, and for 0·04 seconds the transmission from the master is reduced 60 cycles per second. This change locks the green and purple decometers, and lights the red light on the lane identification meter.

During the next half second red lane identification takes place and the lane identification pointers jump to their correct place. The sector pointer indicates which of the six vernier pointers should be read. The pointers will be paralysed in this position for 4 seconds. Normal transmission is resumed for the remaining 14·46 seconds.

At 08h. 00m. 15s. Green identification begins by the master frequency being increased by 60 cycles per second.

FIG. 103.

At 08h. 00m. 30s. Purple identification begins the frequency of the master is reduced 60 cycles per second and then increased 60 cycles per second. This locks red and green decometers and switches on the purple light and purple lane identification takes place.

Normal transmission is resumed until 08h. 01m. 00s. when red identification begins again.

113. Other chains operate in a similar manner but the basic frequency (*i.e.* 1 *f*) has a slightly different value. For example it is 14·167 for the English chain and 14·226 for the Danish chain.

There are now five zones in operation. The coverage of four of them is shown in Fig. 103. The other chain is the German chain.

CHAPTER XV.

USING THE DECCA NAVIGATOR

114. Before sailing.—Half an hour before sailing see that the aerial is properly rigged and that mains are at correct voltage, switch the receiver on.

Select the required chain by rotating the knob on the lower right-hand side of the receiver unit (five for English chain, seven for Danish). The chain in use is shown in the little panel on the left of the indicator unit (Fig. 101). If lane identification is in use, switch it on (see Fig. 102).

Press the " Ref." knob on the green decometer and keeping it pressed adjust all the zero knobs so that the fractional pointers and both pointers of the lane identification decometer are all set at zero.

Still holding the " Ref." knob depressed press the knob marked " Test " on the red decometer. The following *clockwise* movements of the decometer pointers should be observed.

Red, approximately 0·20 lane.
Green, approximately 0·15 lane.
Purple, approximately 0·25 lane.

Lane identification sector pointer = one lane of the red scale.

Set the decometer pointers to the Decca co-ordinates of the ship's position by using the " Re-set " knob on each decometer.

If the Decca co-ordinates are not known they can be found by the lane identification meter.

The decometers should not be re-set because of disagreement on a single lane identification observation but if a consistent error is shown they can confidently be re-set. The most accurate readings are obtained when there is continual agreement between decometers and both the sector and vernier pointers of the lane identification meter.

115. Reliability.—If the Decca transmission were interrupted while the ship changed her position by one lane, then the decometers would slip a lane. With lane identification this would be readily seen. Exceptional precautions are however taken to make Decca as reliable as human ingenuity can contrlve. The transmitting stations are triplicated and are continuously watched (*i.e.* monitored). The ship-borne equipment is well able to stand even the most rigorous conditions, and indeed the Decca Navigator is an instrument of extraordinary reliability.

116. Pattern error.—The Decca charts are drawn on the assumption that there is no distortion in the pattern. This is largely true, but there are some areas where slight distortion is observed, particularly off the Cornish coast and the West coast. Data sheets are issued giving the correction to be applied to the decometer readings.

These give details of systematic error due to pattern distortion, and also discrepancies due to other random causes.

117. Skywave.—It is the groundwave which is wanted in the Decca system. Should the receiver be receiving sky wave as well as ground wave then the two will probably be out of phase, since the sky wave has followed the longer route. The receiver records the resultant wave and considerable error may result.

Beyond 200 miles at night the sky wave effects may cause considerable error and after dark the effective cover is limited to 300 miles or so. By day the pattern can generally be relied on up to 500 miles except in mountainous regions where distortion may occur.

118. Homing.—It should be noticed that in thick weather if many ships regularly " home " along a Decca lane it will result in a concentration of traffic in a very narrow belt.

119. Lane slipping can be caused by interference from other transmitters either ashore or on board, or by a change of generator. When navigating on Decca, frequent readings should be taken and logged when any slip will be noticed immediately.

Any failure in transmission is notified by W/T. In such a case when transmission is resumed the lane number may be incorrect but this can be checked by the lane identification meter.

There may be a phase shift inside the apparatus during the warming up period and it is advisable to have the set running about an hour before it is required.

CHAPTER XVI.

LORAN

120. Loran.—The name is compounded from LOng RANge navigational aid, and the effective range of Loran is about 650 miles by day and 1300 miles by night. A rough idea of its accuracy is to consider that the error will not exceed 1% of the distance from the transmitting station.

Loran is another hyperbolic system using the transmissions of a master and a slave station. The two transmitters are usually at the ends of a long base line (about 200 miles).

The master transmits a short but powerful burst of signal—that is a "pulse"—which lasts for 40 micro-seconds (1 micro-second = 1 μ sec = one millionth of a second). This pulse is received by the slave and after an artificially imposed delay of definite amount is re-transmitted by the slave, both signals being received by the ship. If the ship can accurately time the interval between receiving the master signal and the slave signal, and subtracts the artificial delay, then the resultant time difference will indicate how much longer the path was via the slave and will so fix the ship on a hyperbolic P.L.

The number of pulses transmitted per second is called the Pulse Recurrence Rate (P.R.R.) and is either about 25 or about 33. The artificial delay is always more than half of the pulse recurrence interval.

If the P.R.R. is 25 there is $\frac{1}{25}$ second between pulses and so pulses are separated by $\frac{1}{25} \times$ 186,000 miles (about 7000 miles). If there was no artificial delay the ship would receive master and slave signals fairly close together, but may not be able to distinguish which is which.

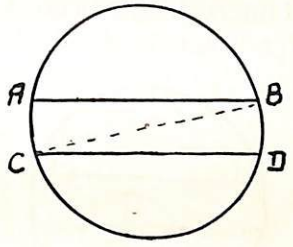


FIG. 104.

The delay being more than half the recurrence interval means that the signals belonging to one pair will be separated by more than $\frac{1}{50}$ second. They will be master ——— slave, master —— slave, and the ship could not compare the slave signal with the following master signal for the interval would be too short.

The signals are received by a special Loran receiver and displayed visually on the face of a cathode ray tube (C.R.T.) giving A type display. Cathode ray tubes are described in the next chapter on Radar.

The bright spot of light caused by the electron stream hitting the face of the C.R.T. is made to perform a double sweep.

The spot goes steadily from A to B, jumps to C, proceeds steadily to D, jumps to A and repeats.

The number of times it does this double sweep in a second is called the sweep recurrence rate. When the signal is received it makes the spot of light jump up and down again. If the sweep recurrence rate is exactly the same as the pulse recurrence rate then these jumps will always occur at the same spot in each sweep and so make a " blip " in the trace.

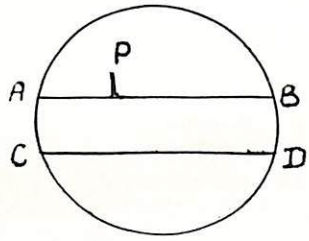


FIG. 105.

If on the first sweep a pulse from the master was received when the trace was at P, then $\frac{1}{25}$ second later the trace has completed its double journey and is back at P, and since a pulse will be coming in from the master every twenty-fifth of a second another jump will occur at P, and due to the persistence of the tube these will be seen as a " blip."

There will be two blips on the trace, one from the master and one from the slave, and it is necessary to determine which is which. There is a knob on the receiver which enables the operator to move the blips horizontally to the left or to the right, by this means it is possible to get one blip on the top line and the other on the bottom line. When this has been done the one to the left will be due to the master, for the interval from master to slave is more than half the total interval. The same knob can be used to move the blips so that the master echo is to the left-hand side of the top trace.

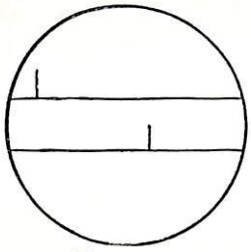


FIG. 106.

Two artificially produced pedestals are produced on the traces (Fig. 107). By turning another knob, which operates a counter it is possible to move the slave echo until its left-hand edge is the same distance from the left-hand edge of the pedestal as the master echo is from the edge of its pedestal. This gives a rough measure of the distance between the echoes, but it is necessary to measure this distance more accurately.

To enable this to be done the speed of the sweep can be increased in stages from slow to medium fast and to fast. When the speed of the sweep is increased it now travels much faster from A to B and from C to D and wastes more time on the journey B to C and D to A. The effect of

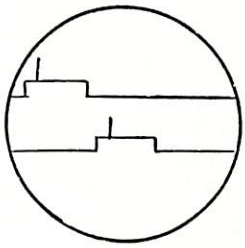


FIG. 107.

this spreads out the blip and makes it possible to set the echoes more accurately. Having adjusted the echoes on the slow they are arranged with their left-hand edges immediately below each other on the medium fast sweep.

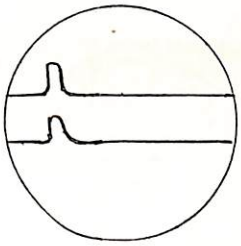


FIG. 108.

The sweep rate is then changed to fast, the two echoes are now superimposed and then left-hand edges carefully fitted. The fast sweep has now spread the blip over most of the tube

Each of these adjustments moves the wheels of the counter and the time can now be read direct from the counter, viz :—3872 micro-seconds.

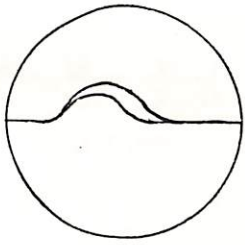


FIG. 109.

This fixes the ship on a hyperbola where the time lag of the slave signal behind the master is 3872 μ seconds, and reference can be made to a Loran lattice chart, the ship will be somewhere on the line numbered 3872.

Stations are identified by their frequency and their P.R.R. Three frequency channels are used 1850, 1900, and 1950 kcs. The two basic

P.R.R.'s are 25 and $33\frac{1}{3}$ called "Low" and "High" respectively, but each range has eight variations.

	0	1	2	3	4	5	6	7
L frequencies	25	$25_{\frac{1}{16}}$	$25_{\frac{2}{16}}$	$25_{\frac{3}{16}}$	$25_{\frac{4}{16}}$	$25_{\frac{5}{16}}$	$25_{\frac{6}{16}}$	$25_{\frac{7}{16}}$
H frequencies	$33\frac{1}{3}$	$33\frac{4}{9}$	$33\frac{5}{9}$	$33\frac{6}{9}$	$33\frac{7}{9}$	$33\frac{8}{9}$	34	$34\frac{1}{9}$

If the identification of a pair of stations is 2 L 3 it means it transmits on No. 2 frequency (1950 kcs.) on the 3rd set of the Low P.R.R., *i.e.* with a P.R.R. of $25_{\frac{3}{16}}$. It is only necessary to set three knobs to 2 L 3 respectively, to tune in this pair of stations. A glance at these three knobs will show which station is being received.

At long ranges the ground wave will be lost and sky wave will be received, it is then necessary to apply a correction, the value of which is printed on the lattice chart.

If the gain is turned up the various echoes can be seen.

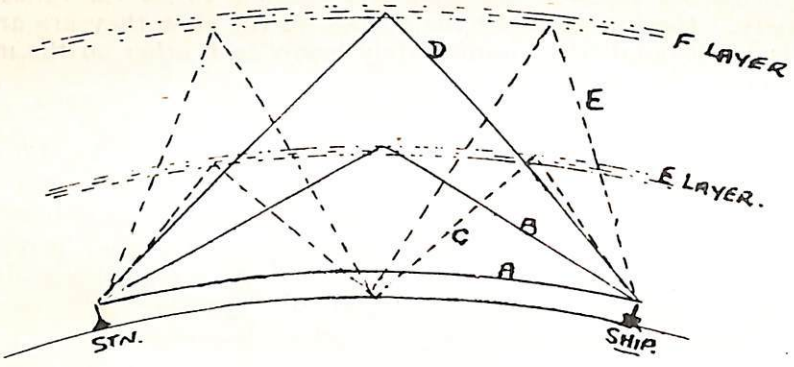


FIG. 110.

Echoes received as the ground wave begins to fade out. A is the ground wave. B is the echo from a single reflection from the E layer. C is the echo received after the wave has been twice reflected by the E layer. D is the first echo from the F layer, and E the twice-reflected echo from the F layer.

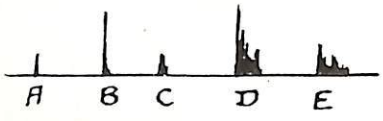


FIG. 111.

Experience enables the operator to identify these different echoes. The ground wave echo is to be preferred but at long ranges this will have disappeared and the sky wave echoes must be used.

If the transmission is unreliable the signal is made to "blink" and the echoes either blink on and off or jump about on the screen. By this means the operator knows that although he is receiving signals they cannot be relied on.

A certain amount of experience is necessary to use a Loran receiver effectively.

121. Brief Summary of Navigational Aids.

Type	Frequency	Day. Max. Range. MLS.	Day. Accuracy 50%	Day. Accuracy 95%	Night. Max. Range MLS.	Night. Accuracy 50%	Night. Accuracy 95%	Remarks
M/F D/F Shipborne	250-600	300	1°	3°	25	1°	3°	Landfall.
Shore	300-600	500	0·7	2°	100 100-500 Over 500	·7° 1·4° ·7°	2° 4° 2°	Ocean and Landfall.
Decca	70-130	300 300-1000	·02° Lower but useful	·05°	0-75 75-200 200	Effective Poorer than day Serious errors over 250		Ocean Landfall and Pilotage.
Consol	200-500	1500	0·2°	0·6°	25-50 350-500	As by day 0·5°	 1·7°	Ocean only.
Loran	1750-1950	600	0·2%	0·6%	0-500 500-1200	0·2% 0·3%	0·6% 0·9%	Ocean and Landfall.

CHAPTER XVII.

CATHODE RAY TUBE (C.R.T)

122. The Cathode Ray Tube (or C.R.T. as we will call it) is a funnel shaped, evacuated glass tube equipped at the narrow end with means of producing a beam of electrons and, at the broad end, a chemical coating, called the screen, which has the property of breaking into fluorescence when struck by this beam of electrons.

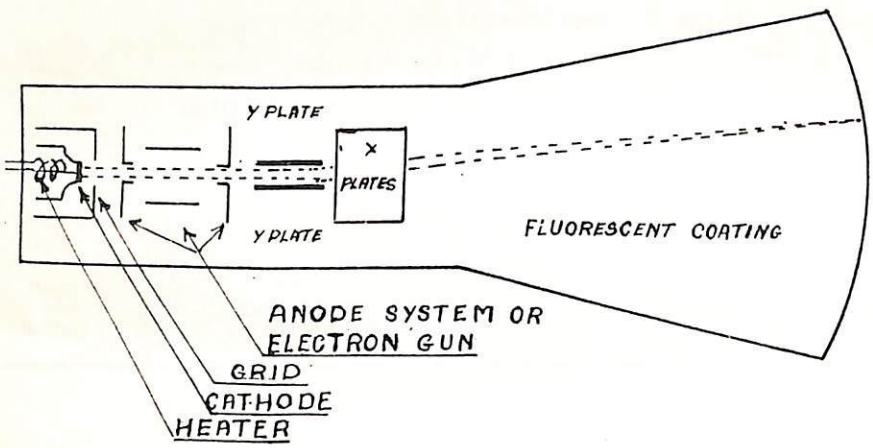


FIG. 112.—Cathode ray tube.

The beam, which is to all intents and purposes weightless, may be deflected in any desired direction and at any desired speed. The method of achieving this will be discussed a little later in this chapter. Firstly we will examine the way this electron beam is produced. The cathode is a disc, coated with a chemical which gives off electrons easily when heated. The grid, or control electrode, is a tube closed at one end by a disc having a hole in it through which the electron beam will pass. The anodes, there are two or three of them, which, collectively, are called the " electron gun," are in the form of discs or tubes of metal or other conducting material.

The grid voltage regulates the density of the electron beam, the less negative it is with respect to the cathode the more dense will be the beam and this will be apparent on the screen by a brightening of the spot. If the grid is made more negative the reverse will apply.

The electron gun (anode system) is highly positive with respect to the cathode and it accelerates the electrons so that they strike the coating on the tube face at high speed.

123. The Coating.—There are several coatings which may be used in C.R.T.s, only two of which need concern us here. They are the short persistence type used in "A" displays (*e.g.* the oscilloscope which may be provided with the set) and medium persistence type used in P.P.I.'s. The latter are more important to the navigator (see § 130). Persistence is the property of the coating to remain in a state of fluorescence for a period after the electron beam has been removed. Another name for this is "Afterglow."

The short persistence tube has a single coat of zinc silicate with a manganese activator (Willemite) and fluoresces with a bright green light which decays rapidly. The medium persistence tube has a double coating. The inside coating, which the electrons strike is of zinc sulphide with silver activator and fluoresces with a brilliant blue light which decays rapidly. The outer coating (next the glass) is of zinc sulphide and cadmium sulphide with a copper activator. This coating is excited by the blue flash of the inner coating and fluoresces with a blue-yellow light and in total darkness this can remain visible for an appreciable time. In some equipments an amber filter is fitted to kill the blue light thus leaving the picture an amber or yellow colour. This relieves eyestrain (tests have shown that the eyestrain occasioned by viewing a Radar screen is the same as that due to reading).

The important feature of the coating so far as the navigator is concerned is that its life is limited and its life depends largely upon the treatment it receives. The grid voltage controls the flow of electrons through the tube, the more dense the electron beam, the brighter the spot and therefore the picture but, unfortunately, at the expense of the chemical coating.

The grid voltage is regulated by the " Brilliance " control which would be adjusted according to the light conditions existing at the time. The lighter the conditions the more will the " Brill " be increased to enable the observer to see the picture. Using the P.P.I. in daylight is therefore a very good way of destroying the coating and rendering the tube useless or dangerous because the coating may fail to respond to echoes from targets near the ship. There is only one way to view a P.P.I. and that is in total darkness or as near thereto as circumstances permit.

124.—Deflection.—There are two methods of deflection or control used in C.R.T.'s (1) Electrostatic control and (2) Electromagnetic control both of which are of concern to us.

Electrostatic Control.—Electrons are negative particles of electricity and will therefore be repelled by a negative charge. If in our C.R.T. a metal plate X is fitted as illustrated (Fig. 113) and a negative voltage is applied to this plate then the electrons moving past it will receive an upward kick as they pass it causing them to alter course and land at position B instead of at the centre of the tube A. The deflection of the spot AB is a measure of the voltage applied to the plate. Increase the voltage and the deflection will increase. Exactly the same effect would be obtained if a second plate were fitted opposite the first one and a positive voltage applied to it. If an alternating voltage were applied to

these plates the spot would move up and down in step with the changing voltage. At a frequency of more than a few cycles per second the spot would appear as a vertical line due to the persistence of the tube, the length of the line being determined by the voltage applied to the plates. Because the spot (beam) is almost weightless it may be moved thousands of times per second if need be.

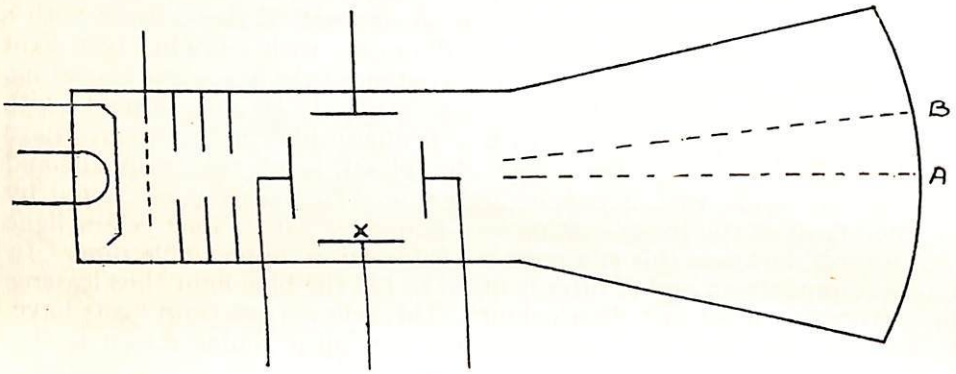


FIG. 113.—Electrostatic deflection.

Another pair of plates fitted at 90° to the first pair would produce the same effects, the spot, of course, would then move in a horizontal direction.

The plates causing the spot to move vertically are called " Y " plates or Vertical Deflection Plates and those causing horizontal movement " X " plates or Horizontal Deflection Plates. By applying voltages to both pairs of plates at the same time the spot may be deflected in any direction.

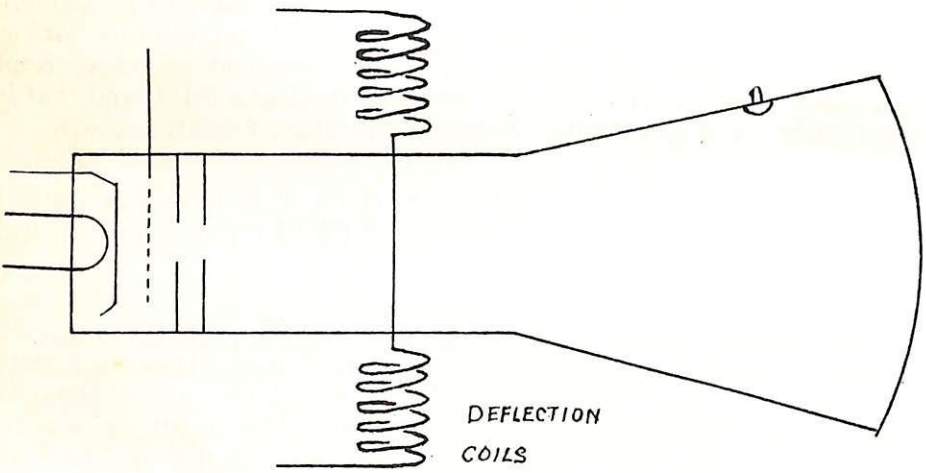


FIG. 114.—Electromagnetic deflection.

Electro-Magnetic Control.—Electrons are affected by magnetic fields in such a way that they experience a force at right angles to their velocity and at right angles to the lines of force of the magnetic field, but,

for the sake of simplicity we will assume that the electrons are attracted by a N. Pole and repelled by a S. Pole.

The electro-magnetic tube has no X and Y plates and if a permanent magnet were placed on the neck of the C.R.T. with its N. pole towards the tube deflection would occur towards the magnet, the amount of deflection depending upon the strength of the magnetic field. The deflection would be away from the magnet if the magnet were reversed. Permanent magnets would give fixed deflections, but if electro-magnets were substituted, then the deflection would depend upon the strength of the current flowing through the magnet coils. If the current were caused to pulsate then the spot would move across the tube face in step with the changing magnetic field. Now let us see how these deflections may be made use of in Radar.

125. The measurement of time intervals.—

THE TRACE is the name given to the line of light left by the moving spot on a C.R.T.

TIME BASE is the name given to a trace which has been divided into units of length representing ti e or to a trace which is related to time.

WAVE FORM.—This is a graph of a changing voltage or current plotted with respect to time.

An important wave form in Radar is the "Sawtooth" and a little time and study given to it will help in understanding the action of time bases.

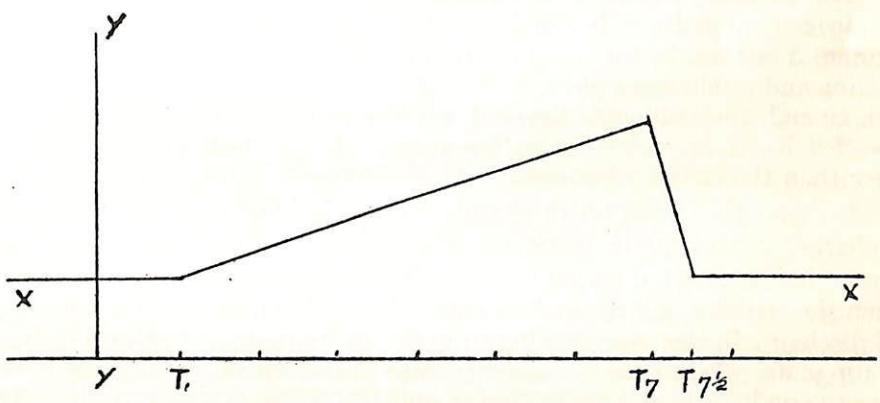


FIG. 115.

The line base line is divided into equal divisions representing time intervals, say $\frac{1}{1000}$ second each and YY is divided into equal divisions representing volts or current. The sketch will give us this information :

(*a*) that the current or voltage in the circuit is steady until time T_1

(*b*) that the voltage or current rises at T_1

(*c*) that it rises uniformly with time until time T_7

(*d*) that at time T_7 the voltage or current falls sharply

(*e*) that the voltage or current is again steady at time $T_{7\frac{1}{2}}$.

The job of a Time Base Generator is to produce a wave form, like the one just described, at regular intervals and, to satisfy our curiosity, let us examine a very simple one.

In this sketch (Fig. 116) R is a resistance which may be variable, C is a condenser, N is a glow discharge lamp or " Neon " bulb.

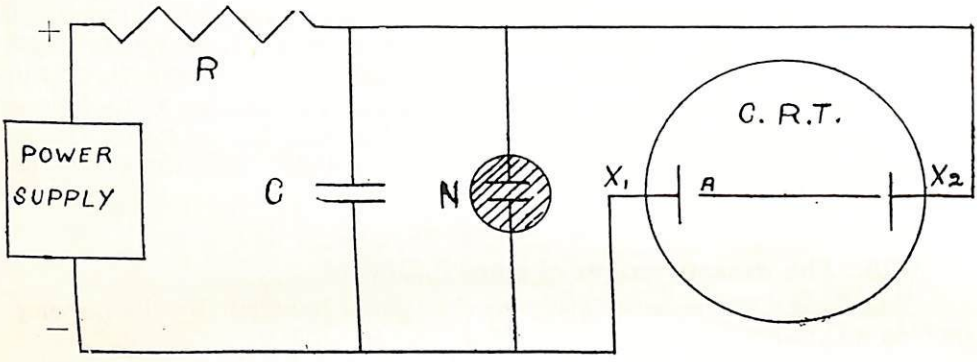


FIG. 116.

A condenser requires a certain time to charge or discharge depending upon the resistance in the circuit and the capacity of the condenser. Its charge curve is like the one shown in Fig. 115.

The property of the neon lamp is that it is a non-conductor until a certain critical voltage is reached, called the striking voltage, when it becomes a fair conductor. Conduction is indicated by the gas in the neon ionizing and producing a glow. Once started the conduction can continue, even though the voltage is lowered, until a voltage is reached, called the cut-off voltage, at which ionization stops. This cut-off voltage is much lower than the striking voltage.

In action the circuit operates thus. On switching on, C will commence to charge, its top plate going more and more positive with time and, because it is connected across C, the voltage across the neon will rise also. When the striking voltage of N is reached it will conduct and, in doing so will discharge C, electrons flowing from the lower plate of C, through N, to the top plate. When the voltage on C falls to the cut-off value of N, N will cease to conduct, C will again charge and the whole action repeats. The wave form at X_1 X_2 will be the same as that of C to which they are connected and will appear as shown in Fig. 117.

To understand this wave form diagram let us assume that the value of X_1 is constant and that the voltage at X_2 will vary with respect to X_1. The diagram shows that the voltage at X_2 will rise with time to the value of B volts (the striking voltage) and then falls to a value of A volts (the cut-off voltage), rises again to B volts and so repeats the performance so long as the circuit is switched on.

To use the circuit, suppose the points X_1 and X_2 are connected to the X plates of an electrostatically controlled C.R.T. on whose face the spot lays normally at position A. As the voltage on X_2 goes positive more and

more the spot will be drawn across the tube face until the maximum voltage is reached, when it will fly back to its original position. This action will be repeated every time C charges and discharges.

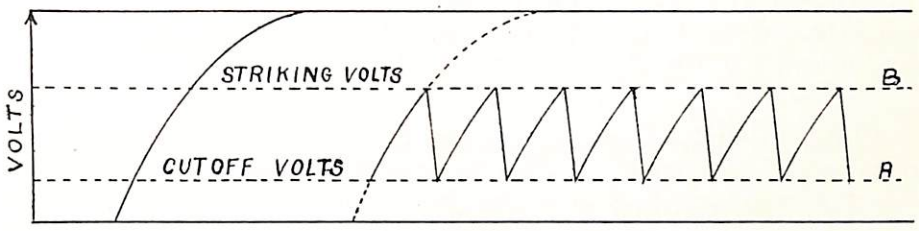


FIG. 117.—Charging curve of condenser.

Now the number of times this action will occur depends upon the value of C and R and let us say that their value is such that the frequency of the wave form is 1000, that is, one complete cycle will last $\frac{1}{1000}$th of a second (1000 μ secs.)* and if the spot moves out in 900 μ secs. and back in 100 μ secs. then the length of the trace represents 900 μ secs. If the spot moved at a uniform speed then, by dividing the trace into nine equal lengths then each division will represent 100 μ secs.

Suppose we wish to know the time between two events, such as a pulse being fired from a transmitter of a radar set as event No. 1, and the return of an echo from a distant target as event No. 2, then we could reason as follows: If, when event No. 1 occurs, a negative-going jab of voltage is applied to the lower Y plate of our C.R.T. then this will cause the spot to jump sharply up and down as it moves across the tube face, thus putting a kink in the trace which marks the time the pulse was sent out. When the echo returns it passes through the receiver and is applied as a negative jab of voltage to the lower Y plate of the C.R.T. where it will cause a second kink to appear in the trace and the distance between kink 1 and kink 2 will represent the time required for the pulse to go out and echo to return. This type of display is called an " A " scan.

In the simple time base circuit just described it will be noticed that the voltage across C does not rise uniformly with time so that the spot will not move across the tube face at a uniform speed. Much more elaborate time base circuits are used in Radar so that the spot may move at a uniform speed. On P.P.I. C.R.T.'s failure to achieve this will result in " Linear Distortion " of the radar picture.

Time base circuits are in two basic forms.

1. *Free running*, such as the one described, and which may be likened to a machine gun which fires as long as the trigger is held.

2. *Triggered time basis* which will fire only once when started. These may be compared to a rifle which will fire only once each time the trigger is pulled.

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* 1000 μ seconds = 1000 micro seconds = 1000 millionths of a second. See "Munro's Electricity and the Magnetic Compass," §2.

In Radar the time base is fired once each time the transmitter fires.

In the case of electromagnetically controlled C.R.T.'s as used in radar as Plan Position Indicators (P.P.I.) the time base circuit produces a sawtooth current form which is fed through the magnetic deflection coils around the neck of the C.R.T. The spot will then move at a steady speed from the centre to the edge of the tube making a radial trace.

126. Focusing.—The electrons pass along the tube in a fairly broad stream and if they impinged upon the coating in this state they would produce a very large spot area and the result would be that individual echoes of targets having close grouping would overlap forming a large patch of light. To enable the picture to be as sharp as possible it is necessary to converge the electron paths so that they come to a focus on the coating. This is done by a focus coil around the neck of the C.R.T. or by an alteration of voltage on one of the anodes. A Focus Control is provided.

CHAPTER XVIII.

RADAR—THE SET

127. Radar.—Although the basic principles of Pulsed Radar are common to all types of installations, their various applications are highly specialised and in the following work only the type known as " Shipborne " or " Surface warning " is dealt with and the remarks concerning it need not necessarily apply to, say, gun control or aircraft ground approach radar.

The word " Radar " is derived from **Ra**dio **D**etection **a**nd **R**ange," but for our purposes it may be regarded as Radio Direction and Range. As this would indicate, the equipment will do two jobs. (*a*) Give the range of a target, and (*b*) give the bearing of a target. A target is the name given to any object which will return an echo.

128. Range.—Let us first consider the principle and method of obtaining the range of a cliff, using sound and a stop-watch.

1. A blast or pulse of sound is sent out from a steam whistle and at the same time the stop-watch is started.

2. The pulse strikes the cliff and an echo is reflected.

3. The echo arrives at the observer's position and at this instant the watch is stopped.

The information now available is that (*a*) a pulse has gone out and the echo of that pulse, reflected by the cliff has returned, (*b*) that it has taken a certain time to do this as indicated by the stop-watch. We may then reason as follows.

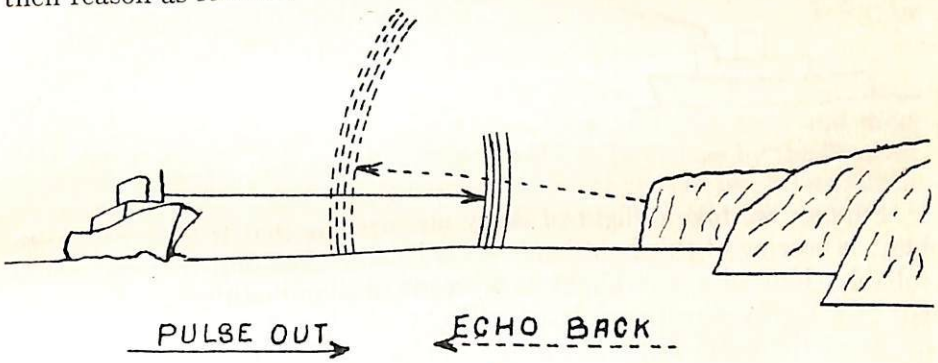


FIG. 118.—Range.

Speed $\times$ Time = Distance, which, in this case, equals the range out plus the range back or 2 $\times$ Range

$$\therefore \quad S \times T = 2R.$$

$$\frac{S \times T}{2} = R.$$

EXAMPLE.—The time between making a blast on a ship's whistle and the return of an echo from a cliff is 4 seconds. What is the range of the cliff taking the speed of sound to be 1100 feet per second ?

$$\frac{S \times T}{2} = \text{Range} \quad \therefore \frac{1100 \times 4}{2} = 2200 \text{ feet.}$$

Now Radar does the same job in the same way but, instead of sound, a pulse of radio energy is sent out and a receiver picks up any echo which may return, the time interval between these two events being measured and given to the observer, in the form of a range on a " Display " unit. More will be said about the display later.

129. Bearing.—Supposing we were asked what was meant by the bearing of an object then we may say that it is the angle between the true meridian and the line along which we look at the object in question. This answer may satisfy our shore-going friends but let us carry the idea a little further. During daylight we see an object, say a lighthouse, because, when it is struck by the sun's rays it becomes a reflector or transmitter of light. Now, light travels in straight lines in any one medium so that only one ray will pass from the lighthouse to our eye and, when taking a bearing, this ray is made to pass through an azimuth mirror, sight vane or polaris mounted on the compass, so what we really measure is the direction from which a ray of light is coming. At night, of course, the sun's rays are substituted by an artificial light which serves the same purpose.

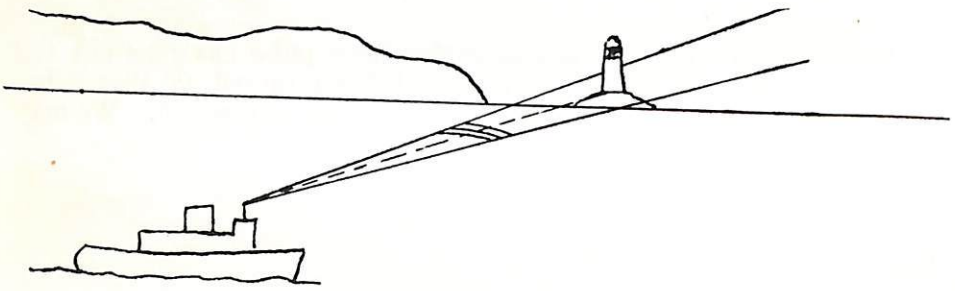


FIG. 119.—Bearing.

Suppose we take a flight of fancy and assume that it is necessary to obtain a bearing of this lighthouse when it is blacked out, then we would probably think of a searchlight as a means of illuminating it. A searchlight is a highly directional beam of light which will ignore any objects outside of the beam but will cause any object inside the beam to reflect light and therefore become visible. If the searchlight were mounted over the compass then it would only be necessary to note the direction in which it points to obtain the bearing of any object within the beam. The more narrow the width of the beam, the more the accuracy of the bearing.

The radar aerial or " Scanner," as it is frequently called, causes the pulses of radio energy which, you will remember, are used for ranging, to be transmitted along a very narrow beam so that, when an echo does

arrive at the receiver, it must have come from some target within the beam. The direction in which the aerial points will be the bearing of the target, which is similar to the searchlight action previously described.

From the foregoing description, we may say that the basic radar set consists of the following :—

1. A transmitter which sends out pulses of radio energy used for ranging.

2. An aerial or " Scanner " which confines these pulses to a highly-directional beam, not unlike a searchlight.

3. A receiver which picks up any echoes reflected by targets within the beam.

4. A " Display " which will give the observer two pieces of information (*a*) the range of the target, and (*b*) the bearing of a target.

There are several types of display, each filling special requirements, but only two are of interest to the navigator. More important of the two is the Plan Position Indicator or P.P.I. The other is called the "A" scan and is described under Cathode Ray Tubes.

130. The P.P.I.—When the transmitter of a radar set fires a pulse a spot of light is started from the centre of a cathode ray tube by the time base circuit and moves radially outwards at a uniform speed leaving behind it a trail of light called the trace. The direction of the trace is aligned to the aerial and if the aerial is made to rotate in azimuth then it will cause the spot to move out on a different azimuth every time the transmitter fires. Because the transmitter fires anything between 500 and 2000 times in one second (Pulse Repetition Frequency) the moving spot appears to be a line of light which rotates round a point at the centre of the P.P.I. in synchronism with the aerial.

Referring to the chapter on Cathode Ray Tubes, it will be seen that a trace may be divided up into units of time and, in radar, time and range are the same thing. When an echo arrives it is picked up by the receiver, amplified and fed to the P.P.I. where it causes the spot to brighten momentarily. It therefore appears as a bright point of light on the P.P.I. whose distance from the centre represents the range and whose bearing may be measured by means of a cursor.

The P.P.I. gives a plan view of what would be visible in a lateral plane.

There are two forms of P.P.I.

1. *The Relative Display*, in which the ship's head is vertically up the C.R.T. (marked zero degrees) and all bearings are relative to the ship's head.

2. *The " True " or " Gyro Stabilized " Display* in which the North point of the picture is vertically up the tube, all bearings then being true.

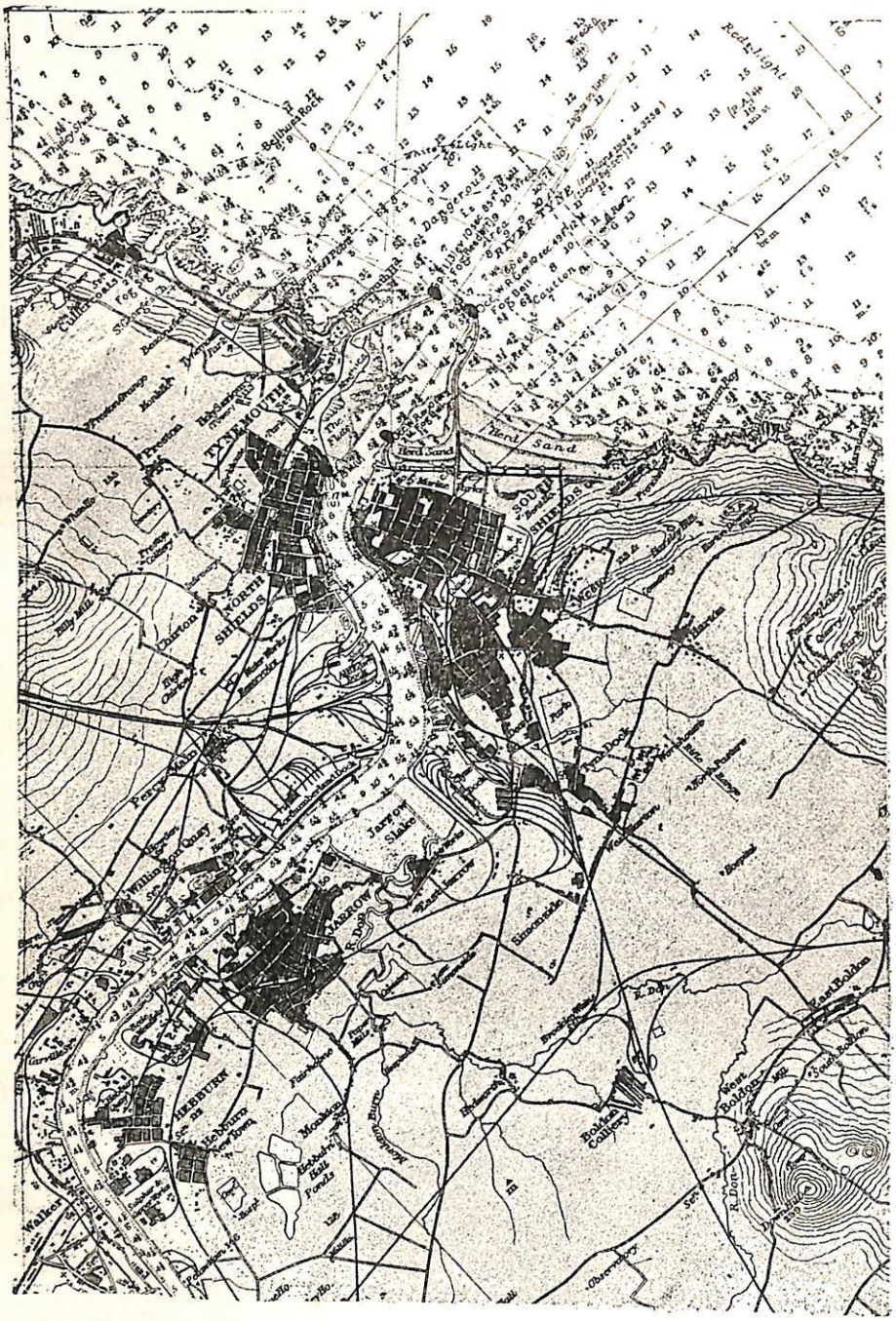


FIG. 120.

Reproduced from British Admiralty Chart No. 3104 with the permission of the Controller of H.M. Stationery Office and of the Hydrographer of the Navy.

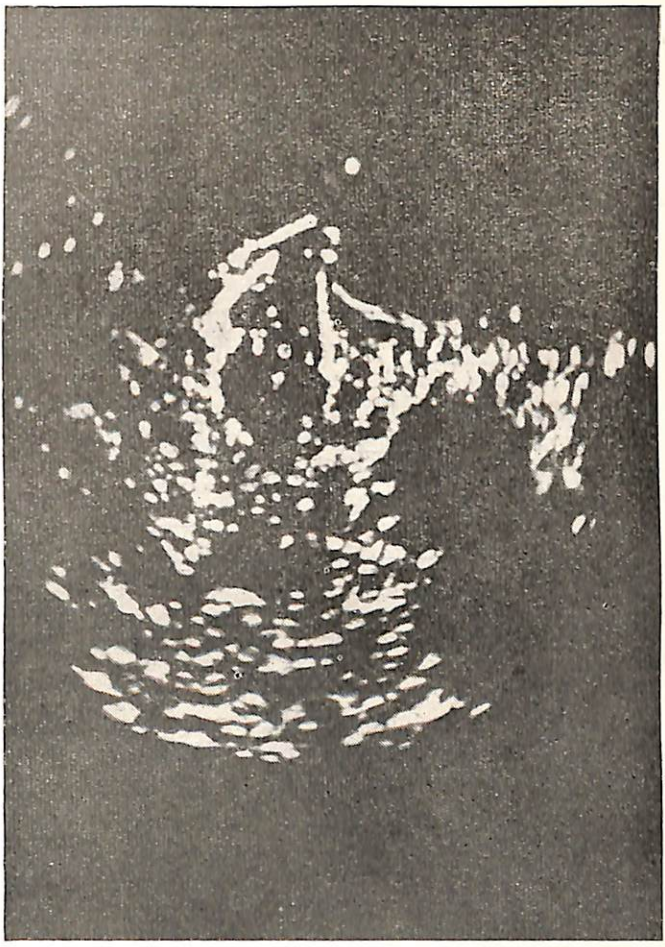


FIG.. 120.

Radar picture on the Screen of Admiralty Pattern 268 set at South Shields Marine and Technical College Radar Station covering area shown on the chart.

131. The Block Diagram.—The Block Diagram is used to show the functions of the various circuits in a radar set. For the purpose of grasping the idea of the major actions occurring in a set the accompanying diagram should be studied in conjunction with the description of each block.

132. The Magnetron.—This is a resonant cavity valve capable of transmitting high power at high frequency. High power is necessary to obtain reasonable echoes from small or distant targets and high frequency is required to obtain narrow beam width.

The magnetron consists of an anode block having a number of cavities drilled or fabricated in it and, at its centre, a cathode. The whole is placed between the poles of a strong permanent magnet, so that the field is along

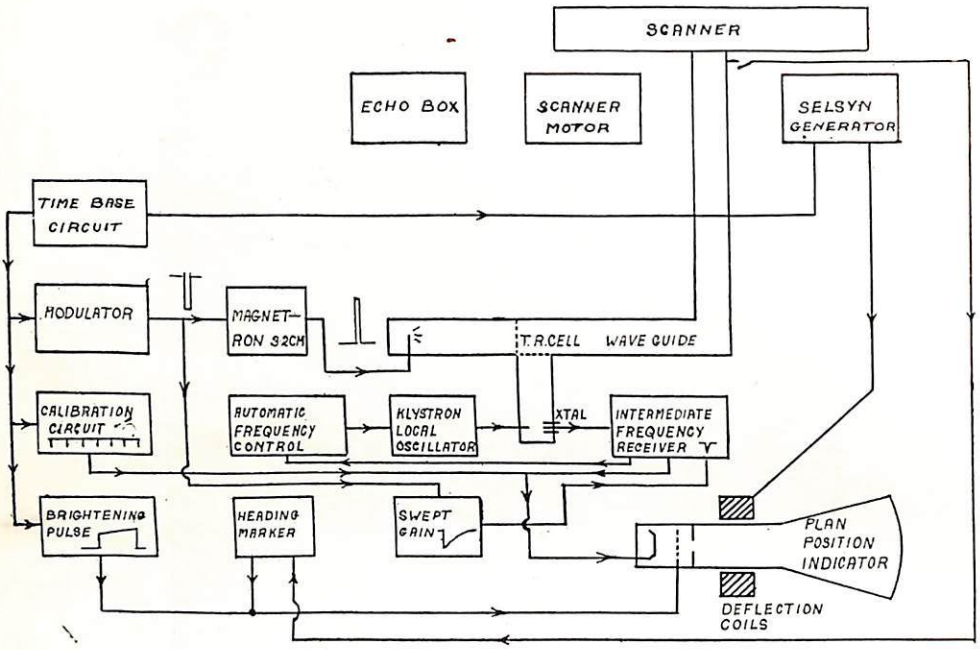


FIG. 121.—Block diagram of Marine Radar.

the axis of the cavities. The action of the device is complicated and it will suffice to state that when the cathode is made very negative with respect to the anode block, the emitted electrons from the cathode move toward the anode block but the magnetic field swirls them round in such a way that they cause the cavities to " Ring," " Oscillate " or " Resonate " at a frequency determined by their size and shape. The high frequency oscillations from the magnetron, which we will call the Magnetron pulse, are fed via a wave guide to the aerial. The Magnetron forms the transmitter of a radar.

133. The Modulator (See § 50).—Modulation means giving the radio wave some intelligence, in telegraphy by breaking it up into dots and dashes, in telephony by making it carry speech or music. In radar it means sending out pulses of an exact shape and power, at regular intervals.

The function of the modulator is to provide a voltage of square shape and very short duration at regular intervals. This voltage which is of high value, many thousands, is applied to the cathode of the magnetron, causing it to fire (transmit) at full power, carry on for a very short space of time and then stop suddenly. This action is necessary to obtain accurate timing for ranging purposes.

The modulator consists mainly of a device, called an " Artificial Line," which will store up electrical energy over a period of time and an electronic switch which allows a rapid discharge of that energy to the magnetron when that unit is required to fire. The electronic switch is usually a net-covered valve called a triggertron or a gas-filled valve called a thyratron (see § 73).

134. The Calibration Circuit.—This circuit provides a series of voltage " pips " or " jabs " with a fixed time interval between them. The first of these pips is coincident with the magnetron pulse and they are applied to the P.P.I. C.R.T. where they cause the spot to brighten at regular intervals as it moves from centre to edge of the tube. As the trace rotates, these bright points upon it leave trails behind them which form the calibration rings. These pips are also applied to the "A" scan, if fitted, where they cause the spot to jump up and down at the same intervals as those on the P.P.I. Though the calibration of the set is adjustable it should not be tampered with. It is advisable to check the accuracy of the calibration by comparing a radar range with a known visual range and noting whether or not the set is over or under-ranging. The time interval may be deduced as follows :—The speed of the electro-magnetic wave is 328 yards per μ sec. so that it will require 3·05 μ secs. for a pulse to travel from a radar set to a target 1000 yards away and a further 3·05 μ secs. for the echo to return to the set so that 6·1 μ secs. will equal 1000 yards range, 12·2 μ secs. will equal 1 mile range and so on.

135. The Variable Range Marker or Strobe Ring.—This is a single calibration ring whose radius may be varied by rotating a wheel or knob. Its purpose is to obtain the range of a target which is between the fixed rings. The range is obtained directly from a scale or counter which is geared to the wheel. Using this device it is only necessary to turn the wheel until the ring cuts the target. Because of the moving component in the circuit it is improbable that it will hold its accuracy over long periods and this should be checked against the fixed rings and adjusted if necessary.

136. The Brightening Pulse Circuit.—The magnetron fires at long intervals compared to the time it takes the spot to go from the centre of the tube to the edge. For example, if a set has a pulse repetition frequency of 1000, that is 1000 pulses per second, then the time between pulses will be $\frac{1}{1000}$ sec. or 1000 μ secs. but, for a 30 mile range, it will require $30 \times 12{\cdot}2 = 366$ μ secs. for the echo to return. It is necessary that the spot should be on the tube during this period, that is, from the time the magnetron fires until the spot leaves the edge of the tube face must be 366 μ secs. The spot is not required outside of this time. One way to achieve this is to hold the C.R.T. grid voltage below cut-off until the magnetron fires when the leading edge of the brightening pulse lifts the grid volts above cut-off thus causing the C.R.T. to conduct and the spot to become visible. Just after the spot has left the tube face the brightening pulse terminates, the C.R.T. grid volts returns to below cut-off so that the spot is invisible during " flyback " and remains so until the next time the magnetron fires.

137. The Receiver.—The purpose of the receiver is to amplify the echoes returning from targets to a power necessary to operate the P.P.I. C.R.T. satisfactorily. The frequency of these echoes will be the same as that of the magnetron, that is, about 9000 mcs.* and no means of amplify-

* 9000 mcs. = 9000 megacycles per second = 9,000,000,000 cycles per second. See " Munro's Electricity and the Magnetic Compass," §2 and §113.

ing the echo at this frequency has yet been developed. To overcome this difficulty the receiver is made to work on the superheterodyne princple which depends on the fact that if two frequencies (let us call them F_1 and F_2) are mixed together they will result in an intermediate frequency (the I.F.) which is always equal to their difference. In short

$$F_1 \sim F_2 = \text{I.F.} \qquad \text{(See § 50).}$$

If F_1 is the echo frequency at, say, 9000 mcs. and F_2 is a frequency produced by a local oscillator within the set at, say, 8960 msc. then the I.F. will be 40 mcs. At this frequency ordinary valves will work and subsequent amplification of the echo may be carried out. The mixer must be able to handle both F_1 and F_2 and uses a crystal and cat's whisker although this is in a modern form and appears to be not unlike a ·22 cartridge with a little probe protruding from one end. These crystals are delicate and should be handled with care. The output of the I.F. amplifier is in the form of a square shaped voltage pulse which, after a further stage of amplification (video amplifier) is applied to the P.P.I. C.R.T. where it causes the spot on the tube face to brighten momentarily so that an echo appears as a bright point of light. It is also applied to the "A" scan, if fitted, where it will cause the spot to jump up and down. So much for the general working of the receiver, and now a pair of particular points about it. Firstly, the power of a radar echo is microscopic and it may be thought that all that is necessary is to add more and more amplifying stages until satisfactory power is obtained. Unfortunately this is not the case because there is no such thing as a " quiet amplifier." This may be demonstrated by tuning a broadcast receiver so that no signals are received and turning up the " Receiver Gain " (volume control) to maximum when it will be found that the loudspeaker is anything but quiet. The " noise " is, in part, due to uneven electron emission at the cathodes of the valves and cannot be avoided. In radar, receiver " noise " is, of course, visible as a speckled effect on the P.P.I. trace when the " Brill " is adjusted just below the point of visibility.

There are several names given to this " noise " among which are " Grass " (from its appearance on an "A" scan), " speckle," and " grain." Noise sets a limit to the amount of amplification which may be done. Each stage will amplify the noise of the previous stage fed into it along with the echo and also add noise of its own making. If the process is carried on too far, there will eventually be as much, if not more, noise than echo. When this state of affairs is reached echoes will not be detected on the P.P.I. due to lack of contrast between noise and echo. The maker sees to it that the receiver is provided with more than sufficient gain and that means of controlling it is provided also (Receiver Gain Control). This control should, for normal use, be set so that there is as much echo for as little noise as possible. No noise on a P.P.I., however, means that the Rec. Gain is too low or the receiver is not doing its work and the picture should be regarded with grave suspicion. The exception to this is when working on a short range with swept gain applied (see swept gain).

The second point concerns F_1 and F_2. The I.F. amplifier is made to work at a particular frequency plus a little either side. For example, between

40 mcs. or 45 mcs. Unless the I.F. amplifier is fed at this frequency then it will not work satisfactorily which will result in no picture or (much more dangerous) a bad picture. Now, F_1 is the echo frequency which will be the same as the magnetron frequency and, as we have already learned, the frequency of the magnetron is determined by the size and shape of its cavities and is not tuneable. The cavities, however, are subject to change due to alteration of temperature, particularly during the warming up period which follows the starting of the set. This will mean that F_1 will drift and, unless something is done about it, the I.F. will also drift, with the result described earlier. To overcome this F_2, the local oscillator frequency, must be altered by the same amount as F_1 so as to keep the I.F. constant at its proper value. This tuning of F_2 may be carried out by hand in all sets and may also be done automatically in most sets.

138. The Local Oscillator.—This is a resonant cavity, tuneable valve which is capable of producing high frequency but only at low power and is used as a local oscillator, giving F_2, in a radar set. Coarse tuning is done by an alteration of size and shape of the cavity by means of a screw while fine tuning is carried out by a variation of voltage on one of its electrodes called the reflector plate. The name of this valve is a Klystron.

139. Automatic Frequency Control (A.F.C.).—The A.F.C. consists mainly of two accurately balanced circuits which will remain in balance, having no output, so long as the I.F. is correct. If the I.F. should drift, due to a change in F_1 or F_2, then these circuits will become unbalanced and an output appears at their terminals. This output is amplified to the correct amount and applied, in the correct polarity to the reflector plate of the Klystron where it alters F_2 by an amount sufficient to restore the I.F. to its proper value. If the A.F.C. should fail the set may be switched to " Manual " and F_2 tuned by hand.

140. The Duplexing System.—The main component of this is a T/R cell (Transmit/Receive) Fig. 121. The system is used in all but one make of set and its function is to enable one wave guide and one aerial to be used for both transmission and reception. During the period of transmission the receiver must be shut down to protect it from the powerful magnetron pulse and during reception the echo must be deflected to the receiver and the magnetron must be blocked off. The action of the receiver in achieving this may be likened to that of a metal door, hinged as shown and lying across the page during transmission, thus protecting the receiver. When transmission ceases the door swings up to the other position deflecting the echo to the receiver and, at the same time, blocking off the transmitter. Because the action described above takes place anything from 500 to 2000 times a second it would be impossible to use a metal door in practice so that the job is done electronically. Just how this is done is beyond the scope of this work.

141. The Swept Gain Circuit and Control.—In anything but smooth water the seas themselves will return echoes which may run the P.P.I. C.R.T. to saturation. In this case it is impossible to detect target echoes in the clutter area due to lack of contrast between echo and background. Clutter may extend to a considerable range depending on the state of sea and it is the purpose of the swept gain circuit to separate target echoes from sea clutter which it can do provided always that the target echo is stronger than the sea clutter. The power of sea echoes falls off rapidly with range. The action of the swept gain circuit is to suppress the gain of the receiver when the magnetron fires and then restore it with time at the same rate at which the clutter falls off so that when the spot reaches the edge of the clutter area the receiver gain is at its normal level. The amount of suppression required will vary with the state of sea and is adjusted by means of the Swept Gain (or anti-clutter) control. The correct setting for this control is so that the sea clutter is only just visible on the P.P.I. This enables any echo stronger than the clutter to be clearly visible. Clutter is usually stronger to windward than to leeward due to the more vertical faces of the seas to windward making more efficient reflectors than the sloping backs of the seas to leeward. Because of this the Swept Gain Control should be continually adjusted when searching a clutter area.

There are two ways in which the vessel may be exposed to danger by the misuse of this control.

1. *Too much suppression.*—This may cause target echoes as well as sea clutter to be suppressed thus placing a blind area around the ship which may have a considerable diameter.

2. *Too little suppression.*—This may cause target echoes to be lost among the clutter.

By adjusting so that clutter is visible we have a guarantee that too much suppression has not been applied.

142. The Performance Monitor.—Some means must be provided so that it may be known that the set is working well or not. Although meters and oscilloscopes are used in servicing, so far as the navigator is concerned the device used is an echo-box. The echo-box is a resonant cavity which is capable of responding to any frequency in the radar band and is mounted on the mainmast, funnel, or on the aerial pedestal. When the aerial faces the echo-box the magnetron pulse will strike it and cause it to " ring." This ringing continues over a period of time, just as that of a ship's bell would do, at an ever-decreasing power. The stronger the pulse the louder and longer the box will ring. The ringing is re-radiated by the box and is fed to the receiver via the aerial and wave guide. It is displayed on the P.P.I. as a " feather " or " plume," that is, a narrow sector of continuous but weakening echo on the P.P.I. about 0·5 to 1 mile long. Any weakening of magnetron pulse will cause the box to ring less powerfully and for a shorter period thus shortening the feather. If the receiver should fail to amplify efficiently then the feather will again be

shortened. The feather length is therefore an overall measure of the set's performance. Its length should be noted when the set is known to be working well and used as a reference for future occasions. The echo-box permits the observer to know quickly, easily and with reasonable certainty whether or not the set's performance is up to standard, particularly when there are no echoes on the screen. A word of caution about it. The feather is easily seen and measured on a short range. Let us say that it is 7 cables, then this will represent $\frac{7}{10}$ of a one-mile range so that any future shortening of the feather will be immediately apparent. On the 30-mile range the feather will be $\frac{7}{300}$ of the P.P.I. radius and any alteration in the length will be most difficult to detect. If much sea clutter is present then the action of the swept gain circuit will cause the feather to shorten or even disappear but in this case the clutter itself may be used to assess the performance. The sector of the P.P.I. that the feather occupies will be on the bearing of the aerial at the time the box is excited and this direction should be arranged so that the feather falls in a blind sector well abaft the beam or astern (see § 163).

143. The Heading Marker.—This is a line of light running from centre to edge of the P.P.I. and appears every time the aerial faces dead ahead. Its purpose is to enable the observer to determine quickly and certainly whether or not the aerial and P.P.I. picture are in alignment. That is, if Relative display is being used the heading marker should be at zero degrees. If True display is in use the heading marker should indicate the ship's head true. If this is not the case then the control provided to rotate the picture should be used. There is in the aerial mount a cam-operated switch which makes when the aerial is ahead and the effect of this is to cause the trace to brighten thus producing the line of light. The position of the switch relative to the cam is set when the radar is installed. Care must be taken to see that, when an aerial has been sited off the centre line of the ship, the switch works when the aerial bearing is parallel to the fore and aft line of the vessel and not when it is facing the stem head otherwise a constant error in bearing will result. Obvious ? Well, it has been done before !

144. The Deflection System (Selsyn or Magslip).—Please refer to the C.R.T. earlier in the work. In this we learned that the cathode ray was subject to the influence of magnetic fields and that a time base circuit can be made to produce a steadily-rising current which will, when fed through suitable deflection coils, cause the spot to travel steadily from centre to edge of a P.P.I. C.R.T. The deflection system consists of a generator mechanically coupled to the aerial, the deflection coils around the neck of the P.P.I. C.R.T. and a time base circuit. The function of these units is to produce a pulsating, rotating magnetic field around the neck of the P.P.I. C.R.T. which will deflect the spot from centre to edge of the P.P.I., at a uniform speed every time the magnetron fires, and on an azimuth which will correspond to that of the aerial.

145. The Wave Guide.—This is an rectangular section copper tube which is used to carry the pulses from the magnetron to the aerial and to carry the echoes from the aerial to the receiver. It must not suffer damage, from internal dirt nor from internal dampness. Though it is sealed at both ends it is as well to check the tightness of the couplings periodically.

146. The Aerial.—To obtain an idea of the action of the aerial let us consider what is done to obtain a narrow beam using a light wave. The light is radiated from a focal point, or as near a point as possible and a reflector is arranged so that the light is confined to the very narrow, conical beam familiar to us in Aldis lamps, searchlights, headlights, etc. The requirements for a radar aerial are, however, not quite the same as the lights mentioned and though the narrow beam is required in the horizontal sense to obtain good bearing accuracy and bearing discrimination, the beam must be wide in the vertical sense so that a target may be held while

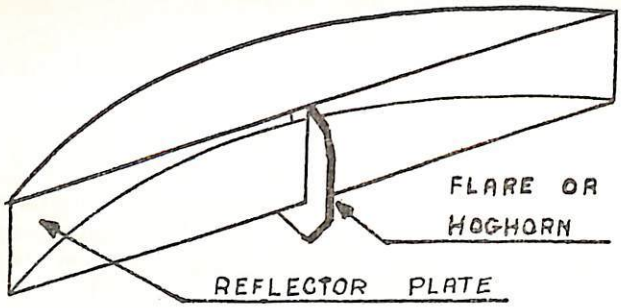


FIG. 122.—Scanner.

the ship is rolling. If this were not so the beam would be lifted off the surface when rolling or pitching and the effectiveness of the radar would be doubtful. To obtain the required result, only the central slice of the full reflector is used as shown. The reflector plate must be kept free of dints, damage, dirt, brush marks, ice, etc., or the efficiency will be reduced. The aerial is double-acting in this way, that when the echoes return to it they will be concentrated at the focal point which is, of course, the wave guide flare (hog horn).

CHAPTER XIX.

RADAR TERMS

147. Pulse Length.—This is the time occupied in transmitting one pulse expressed in μ secs. It is about 0·1 μ secs. or 0·2 μ secs. in commercial radar.

148. Pulse Repetition Frequency.—This is the number of pulses fired in one second and is 500 to 2000.

149. Peak Power.—This is the power transmitted in one pulse and is between 7 kw. and 60 kw. depending on the make of set.

150. Total Power.—This is the total drain of power from the ship's mains taken by the radar and should not exceed 5 kw.

151. Minimum Range.—This is the closest distance that a target remains visible and should not exceed 50 yards for a small object (*e.g.* a second class buoy).

It depends mainly on the pulse length as follows. During the period of transmission the receiver is shut down by the Duplex System for its own protection so that any echo which may return during this time cannot be received and will not, therefore, be displayed. Theoretically the earliest time that an echo may be received will be at the instant that transmission ceases and in order to return an echo at this time a target must be $\frac{PL \times 328}{2}$ yards away (see § 134).

EXAMPLE.—Suppose a set has a pulse length of 0·2 μ ses. then the leading edge of the pulse will have travelled a distance of 0·2 × 328 yards or 65·6 yards by the time the trailing edge is leaving the set, and this will be the physical length of the pulse in space. To return an echo from the theoretical minimum range a target must be a half pulse length away, that is 32·8 yards in this case.

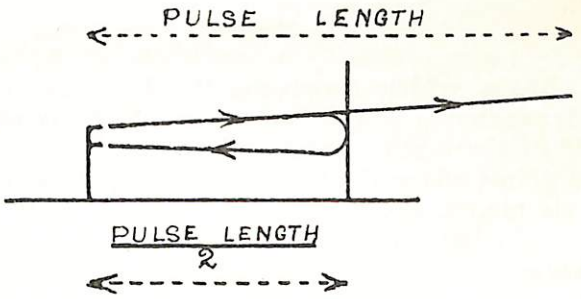


FIG. 123.—Theoretical Minimum Range.

In practice the theoretical minimum range is increased due to the time required for the duplex system to operate and the receiver to recover.

152. Theoretical Maximum Range.—This is the range at which a target must be in order to return an echo just as the next pulse is being fired. It depends upon the time between pulses, which, in turn, depends upon the pulse repetition frequency.

Suppose a set has a pulse repetition frequency of 1000 then the time between pulses will be $\frac{1}{1000}$ seconds or 1000 μ secs. The theoretical maximum range will then be

$$\frac{\text{Speed} \times \text{time between pulses}}{2}$$

$$\frac{328 \times 1000}{2} \text{ yards}$$

$$\text{or } \frac{328 \times 1000}{2 \times 2000} \text{ nautical miles} = 82 \text{ nautical miles}$$

from which range an echo would not normally be expected.

153. Practical Maximum Range.—There are too many variable factors involved to state what the maximum range of a set will be at any given time, but under ordinary conditions it may be expected to give clear indication of the following when the aerial height above water is 40 feet.

Coastlines.—

At 20 miles when ground rises to 200 feet.
At 7 miles when ground rises to 20 feet.

Surface Objects.—

At 7 miles on a tramp of 5000 tons g.r.t.
At 3 miles on a fishing vessel of length 30 feet.
At 2 miles on a typical second class buoy.

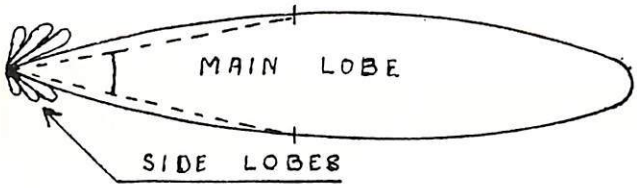


FIG. 124.—Horizontal Beam Width.

154. Beam width (horizontal).—In a radar beam the power intensity is maximum at the aerial and falls away at either side of the centre line of the beam and also along the length of the beam. If a number of points where the power intensity is half the maximum power intensity are plotted and a line drawn through them the resulting shape is a number of lobes. The largest is the Main Lobe and the smaller ones are Side Lobes.

The beam width is the angle between the two lines drawn from the aerial to two points situated on the sides of the main lobe at a sufficiently great distance from the aerial.

The beam width in marine radars is about 2°.

155. Beam width (vertical).—This is made between 20° and 30° to enable a target to be held while rolling.

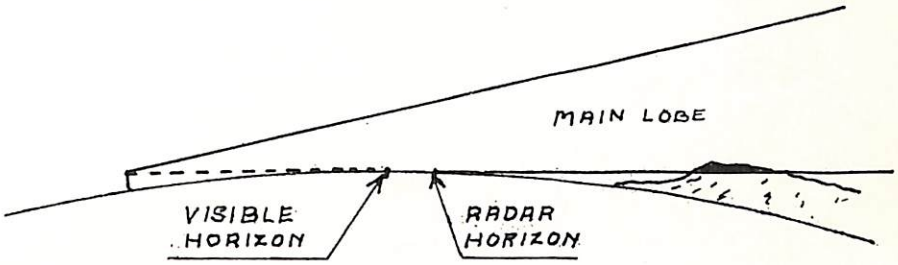


FIG. 125.—Vertical Beam Width.

156. Bearing accuracy.—This depends on the horizontal beam width, the narrower the beam the better the accuracy will be. In marine radars this is ± 1° when the echo is at the edge of the display.

157. Bearing discrimination.—This is the ability of the radar to distinguish between two objects at the same range but on different bearings. It depends upon the beam width and must be such that the set shall indicate clearly the presence of two objects at the same range, when the gap between them subtends an angle of 3° provided the distance between them is greater than 200 feet.

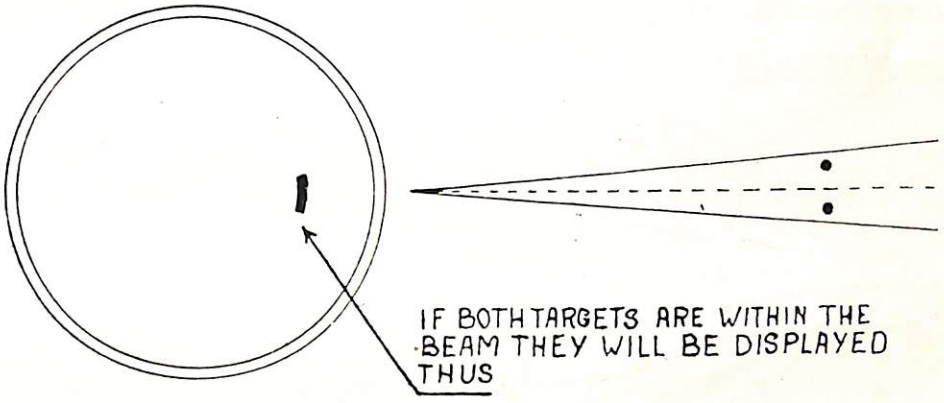


FIG. 126.—Bearing discrimination.

158. Range Accuracy.—The set shall have means provided to estimate the range of any object directly with an error not greater than ± 5% of the maximum range of the scale in use. This accuracy shall be obtainable down to a minimum range of 300 yards.

159. Range Discrimination.—This is the ability of a radar set to distinguish between two targets on the same bearing but at different ranges. It depends upon the pulse length and must be such that the set shall indicate clearly, on the most open scale provided, the presence of two small objects in line when these are 100 yards apart.

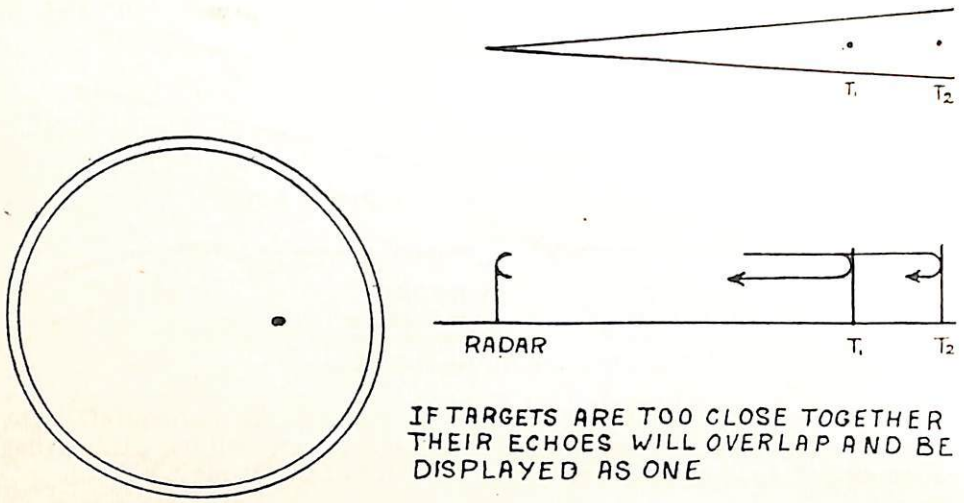


FIG. 127.—Range discrimination.

160. Side Lobes.—These are unwanted lobes situated either side of the main lobe and are capable of returning echoes, particularly of larger targets at fairly close range. The echoes due to side lobe will be displayed at the correct range but on the bearing of the main lobe. Because range is correct side lobe effect must always appear on an arc of a circle having the centre of the P.P.I. as centre.

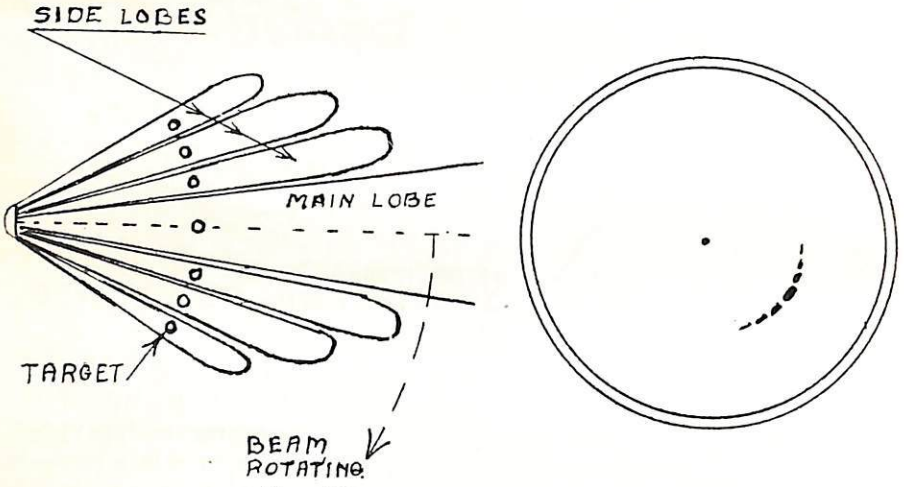


FIG. 128.—Side Lobe effect.

The effect of side lobes may be minimised by carefully reducing the receiver gain when the weaker side lobe echoes will fade out leaving the main lobe echo clearly visible. When this is done care must be taken to remember that small, genuine echoes may also fade out and that the Receiver Gain must be restored to its normal level when attention is directed elsewhere.

161. Reflected or Indirect Echoes.—These are caused by the outgoing pulse striking some part of the ship's structure and being reflected in such a way that it strikes a target. The echo will return over the same path and will be displayed at range aerial-to-structure plus structure-to-target but on the bearing of the main lobe. Because the distance aerial-to-structure is small it may be neglected and it can then be said that reflected echoes are displayed at the correct range but on the wrong bearing.

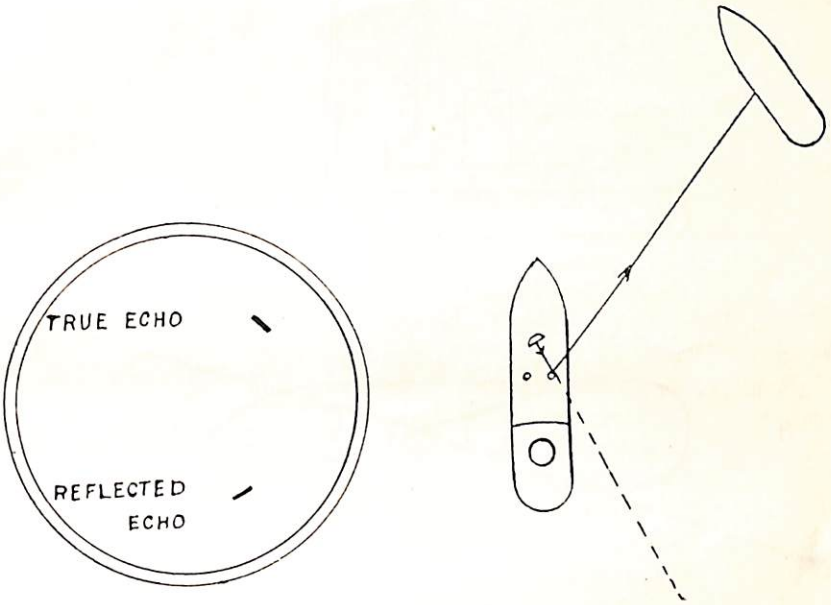


FIG. 129.—Reflected Echoes.

162. Multiple Echoes.—These are caused by the pulse being reflected back and forth between own vessel and a target. The occurance of multiple echoes is more probable with large targets at close ranges. Each echo is displayed on the correct bearing but at a range which is a multiple of the first one.

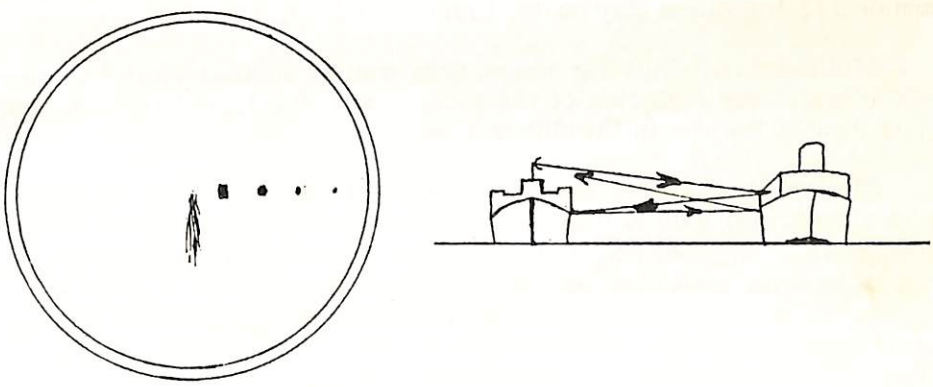


FIG. 130.—Multiple Echoes.

163. Blind and Shadow Sectors.—If any part of the ship's structure should partly block the passage of the outgoing pulse and returning echo the detection ranges in the sector will be reduced (shadow sector). If the pulse is totally blocked then the detection range will be zero (blind sector). Funnels and crosstrees, which are wide compared with the aerial, frequently cause blind sectors while masts, sampson posts, etc., cause shadow sectors.

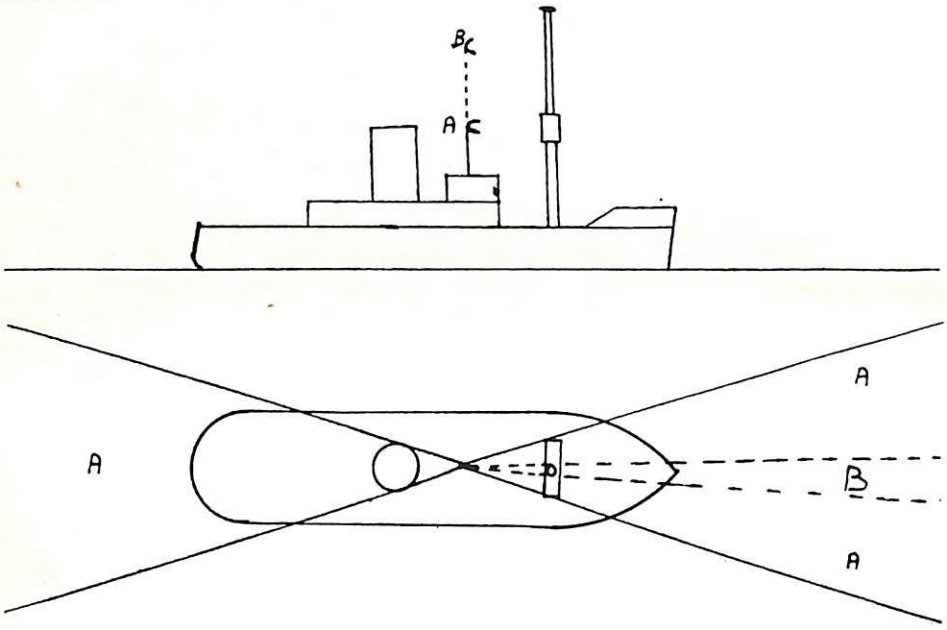


FIG. 131.—Blind Sectors and Shadow Sectors.

A.—Blind Sectors. B.—Shadow Sectors.

With scanner in position A both funnel and crosstrees will cause blind sectors but with scanner in position B only the foretopmast will obstruct the pulse and cause a shadow sector.

The position of these sectors may be estimated by reference to the ship's plan and profile when a set is being installed, but when a set has been installed their position may be determined as follows.

Method 1.—Adjust the swept gain control so that clutter is just visible when any reduction of the pulse power due to obstructions will show as a dark sector in the clutter area.

Method 2.—Observe the echo of a small target crossing the screen with the receiver gain adjusted so that it is just visible. Where it disappears and re-appears will mark the edges of the sectors. This must, of course, be carried out over 360° of azimuth.

In the first method, which is a convenient ready-use one, a shadow sector may escape notice because clutter is generally stronger to windward than to leeward so that the same swept gain setting will not serve for both directions.

In the second method both aspect and range of the object may vary giving varying echo powers so that it cannot be carried out with a single setting of receiver gain. The observer may then be in doubt, when the echo disappears, whether the cause was a shadow sector or a reduction of Receiver Gain.

The following method is tedious but will give results. Suppose, with the ship anchored, a lifeboat is launched and the person in charge instructed to go round the ship keeping a fixed distance off by sextant angle of the funnel, then because range and aspect are constant the echo power will also be constant and a single setting of the Receiver Gain may be used. An alternative to this is to observe a fixed object with Receiver Gain set so that it is just visible and swing the ship through 360° noting where the echo disappears and reappears.

The position of these sectors should be observed for both light and load condition of the ship, entered in the Radar Log, and made available to the observer.

Where blind sectors cannot be avoided the possibility of another vessel approaching down the sector on a collision course (no change in bearing) may be eliminated by " snaking " the ship. This means allowing the ship to drift slowly either side of a mean course by an amount at least equal to half the width of the blind sector.

164. Shadow Regions or Areas.—These are caused by the pulse being obstructed by a target such as a hill or headland beyond which the detection range will be reduced or, if the obstruction is total, then there will be no radar visibility in way of the obstruction. In short, the set cannot see round corners.

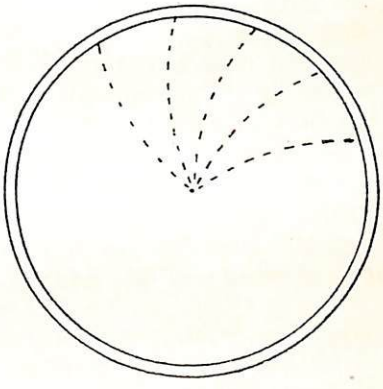


FIG. 132.—Radar Interference.

165. Interference.—If another vessel's radar transmits at a frequency which is at, or near, the frequency of our radar then our receiver will readily accept the pulses from the other vessel and display them on the P.P.I.

Suppose that the P.R.F.'s of both sets are exactly the same and that the other vessel's pulse occured a little time after ours then the point would be apparent at a constant range, and the rotating trace would cause these

points to appear as a circle or an arc of a circle. In practice this is most unlikely to happen because P.R.F.'s do not remain exactly constant but vary slightly round a mean value.

A typical case may occur as follows : If the other vessel's P.R.F. is slightly lower than ours then the point will appear a little further along our trace each time and the interference will be presented as a curved dotted line. If the other vessel's P.R.F. is higher than our own then the curve will be reversed.

Interference is always more apparent on a long range than on a short one because of the spot speed. On a long range the spot travels slowly in comparison to the high speed of spot on a short one, hence the little dots forming the interference effect will be closer together on the long range and there will be more of them. The short range has the dots so far apart that it is not usual to be able to detect a pattern and the dot positions appear to be random so that it is not difficult to confuse them with target echoes. The directions taken by the curved lines on the longer ranges is never constant so that it is unwise to assume that one particular vessel shown on the P.P.I. must be the vessel causing the interference and therefore using her radar. .Nor can we say that lack of interference is an indication that another vessel is not using radar. Interference is more a nuisance than a danger.

CHAPTER XX.

RADAR WAVES

166. Propagation of Waves.—If an ordinary aerial were to transmit a pulse in free space, that is, clear of the earth's surface, then that pulse would be transmitted in all directions. The pulse may be visualised as being concentrated on the surface of a sphere, having the aerial at centre, and whose radius is increasing at 328 yards per μ sec. The power per unit area on this sphere will decrease as the area of the sphere increases. The power per unit area on a sphere having one area will be twice that of the power per unit area on a sphere of twice the area of the first. The power of the pulse is inversely proportional to the square of the radius (Range). This also holds good for beamed transmissions.

167. Attenuation.—This is due to the energy of the radio wave being absorbed and/or scattered by the atmosphere, precipitation, dust and sand storms. At the wave length used in radar, the attenuation due to the atmosphere is not great. Fog, however, causes a reduction in detection range depending on its water content and temperature. In cold regions attenuation due to fog is greater than for those of warm regions. With fogs causing a visibility of 100 yards and less the detection ranges, due to the attenuation of the radar wave, may be much reduced particularly with larger targets. Though fog particles do scatter the radar pulse and echoes from targets, they themselves do not usually reflect enough energy back to the set to cause any indication of their presence on the P.P.I.

Rain can cause considerable scattering and will also radiate enough energy to give a very clear indication of its presence on the P.P.I. unless it is light and uniformly spread over a large area so that there is no contrast between clutter on the P.P.I. and its background. The amount of attenuation and clutter depends upon the rate of precipitation. It is most for cumulo-nimbus rainfall and tropical rain. Rain is not often uniform in density over large areas and the less uniform it is the more easily it is detected upon the P.P.I.

Targets on the far side of a rain area will have their detection ranges reduced and targets within a rain area will have their detection ranges reduced more than those on the far side because the contrast between echo and clutter background on the P.P.I. will be reduced. Rain squalls often saturate the P.P.I. with clutter, that is, light up the tube face in the clutter area as much as the circuitry of the set will permit, so that it will then be impossible to detect a target echo in the saturated area. To search such an area the receiver gain should be carefully reduced so that the weaker rain clutter will fade out leaving the echo of a target, if any, which is stronger than the rain returns, clearly visible. A skilful use of the Receiver Gain control is called for here.

The effect of hail and snow is similar to that of rain but to a much lesser degree.

The effect of dust and sandstorms is, so far as is yet known, similar to fog. Clouds do not return echoes unless there is precipitation within them.

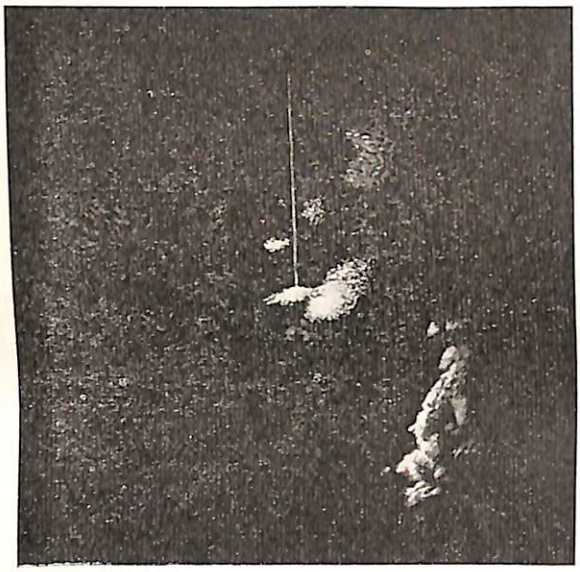


FIG. 133.

Fog and dust storms are least troublesome to radar detection ranges, at worst about 20% reduction, while Tropical rainstorms are most troublesome and, at worst, will reduce detection ranges by about 40% if the target is beyond the squall, and by about 60% if it is within the squall.

168. Refraction.—The radar wave may be regarded as being very similar to the light wave and following the same laws. The radar wave is normally refracted so that it follows the curvature of the earth a little more than a light wave so that the radar horizon is about 6% greater than the visible horizon for similar heights of aerial and eye.

169. Sub-refraction.—This is a shortening of the radar horizon caused by the pulse being refracted away from the earth's surface. Its effect is to reduce detection ranges particularly of low targets. The conditions under which it occurs are those where the temperature falls more rapidly with height than normal and/or where relative humidity increases with height. Cold air over a warm sea will produce this, and may be expected near mountainous coasts where katabatic winds prevail.

170. Super-refraction.—This is an extension of the radar horizon caused by the pulse being refracted so that it follows the earth's curvature more than normal. Its effect is to increase detection ranges and the con-

ditions under which it occurs are those where temperature either rises with height, falls less rapidly than normal and/or a decrease of relative humidity with height. In some cases reflection may occur at the upper limit of the inversion, the reflected ray eventually reaching the Earth's surface. This process can repeat and cause the pulse to follow the earth's surface for phenomenal distances. This condition is known as "ducting" or "trapping" (the pulse is trapped in a radar duct).

Both sub and super-refraction are termed "non-standard propagation" and are not very apparent in mid-ocean except in anti-cyclonic areas and trade wind areas where super-refraction may be experienced. In narrow or coastal waters where warm air extends over a cold sea super-refraction may be expected.

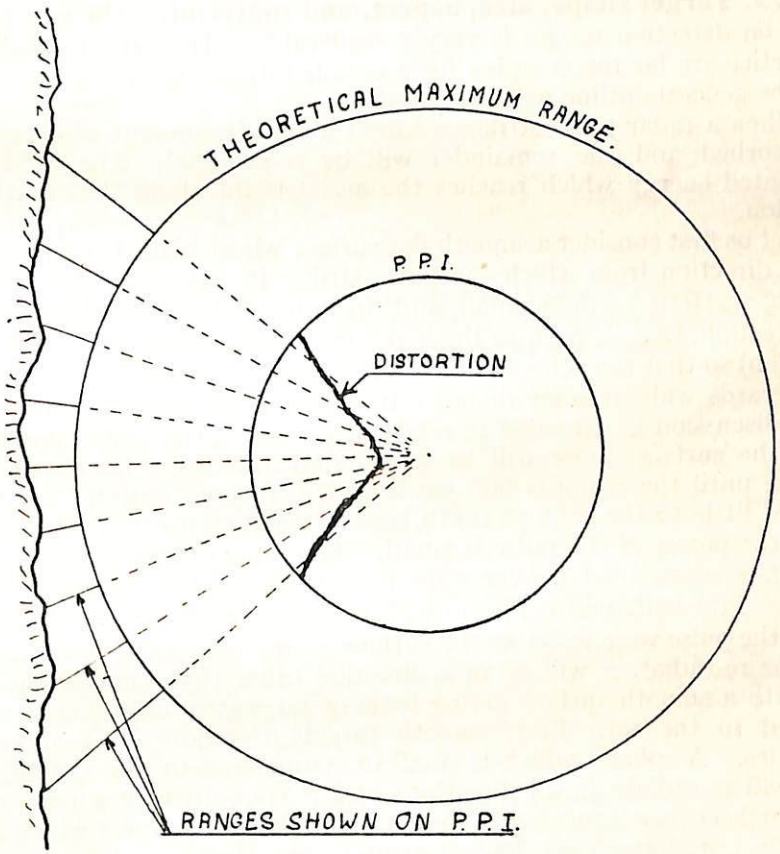


FIG. 134.—Land as Second Trace Echo.

171. Second trace echoes.—These are caused by the echo from a target arriving back at the set after a second pulse has been fired. They will be displayed on the correct bearing but at a range corresponding to the difference between the theoretical maximum range of the set and the true

range of the target. For example, suppose a set has a P.R.F. of 500 then its theoretical maximum range will be

$$\frac{S \times \text{time between pulses}}{2}$$

$$\frac{328}{2} \times \frac{1{,}000{,}000}{500} \times \frac{1}{2000} = 164 \text{ miles.}$$

And, under conditions of Radar Duct, an echo returns from a target at range 165 miles then it will arrive at the set 12·2 μ secs. after the next pulse has been fired and will be displayed at range one mile on the trace belonging to the second pulse (second trace). Land as a second trace echo can be much distorted.

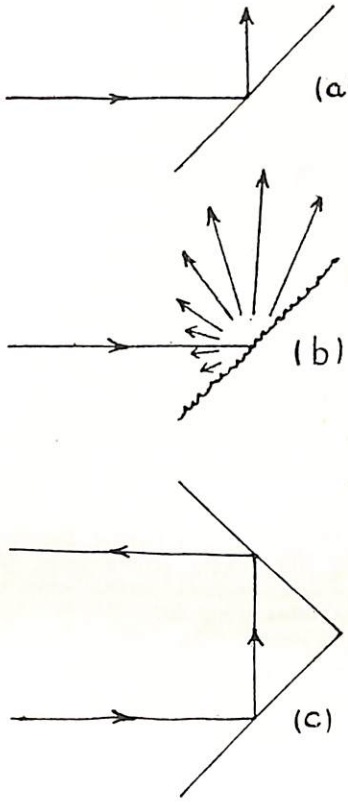
172. Target shape, size, aspect, and material.—The effect of the above on detection ranges is very considerable. The targets dealt with in practice are far too complex for a detailed discussion in this work and only the general outline will be described.

When a radar pulse strikes a target a certain amount of energy will be absorbed and the remainder will be re-radiated. The amount of re-radiated energy which reaches the aerial is the thing that matters in detection.

Let us first consider a smooth flat surface whose plane is perpendicular to the direction from which the pulse strikes it. Because the surface is smooth, scattering will be small, and the bulk of the re-radiation will be in one direction, that is, back to the aerial (angle of incidence equals angle of reflection) so that the echo strength will be good. Suppose that the beam is 500 yards wide at some distance from the aerial and that the surface under discussion is extended in a lateral direction, then more energy will strike the surface, more will be re-radiated and the echo strength will increase until the plane is 500 yards wide. Any extension beyond this will add little to the echo strength because the extension is into a region where the power of the pulse is small. The same argument will apply if the surface is extended in a vertical sense but the limit is very much greater because of the wide vertical beam width used in radar.

If the pulse were to strike the surface at an angle to the perpendicular then the re-radiation will be in a direction other than that of the aerial and, with a smooth surface giving little or no scattering, no echo will be returned to the set. Flat, smooth targets therefore have directional properties. A sphere, which is small in comparison to the section of the beam will re-radiate in all directions and is consequently a poor target, only a little energy returning to the set. A cylindrical object which stands vertically re-radiates over 360° of azimuth but there is a line contact up the side of the cylinder which will give a fairly good echo strength. Circular section tapered objects give poor results because the line contact will return energy in the azimuth of the aerial, but also upwards so that the bulk of the power passes above the aerial.

Rough surfaces produce more scattering than reflection and are not so directive as smooth ones consequently changing aspect of a rough surface does not greatly alter the echo power.



(a) Smooth plane surface will give specular reflections. Little or no echo will return except when struck at 90° when echo will be strong.

(b) Rough surface causes scattering and a fair amount of echo is returned.

(c) The effect of two plane surfaces at 90° to each other is to cause strong echoes over the 90°. This is used in Radar Reflectors.

(d) A sphere re-radiates the radar pulse in all directions and returns little echo. Bad target.

(e) A cone shape is a poor target.

FIG. 135.—Target Response.

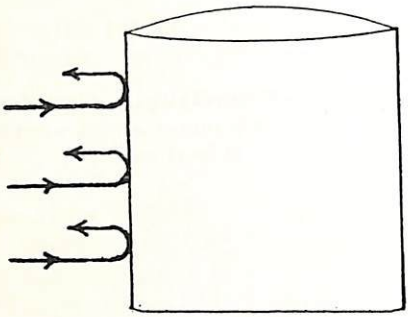


FIG. 135 (f).—Cylinder—Fair echo if high.

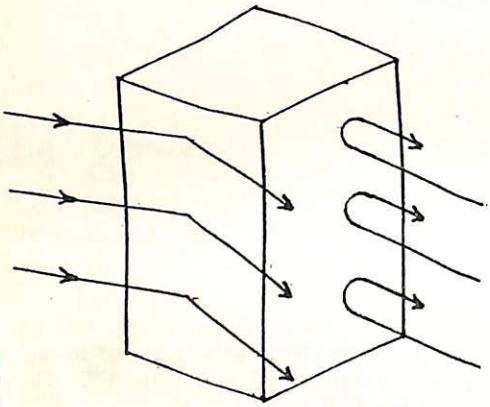


FIG. 135 (g).—Target having directional properties — very strong echo when direction of pulse is perpendicular to a face, otherwise poor.

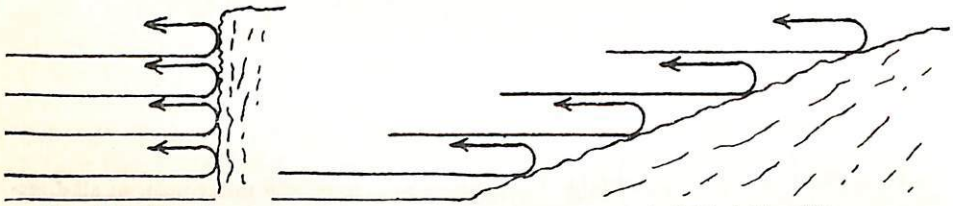


FIG. 135 (h).—Vertical cliff—very good echo. Increase of cliff height will increase echo strength.

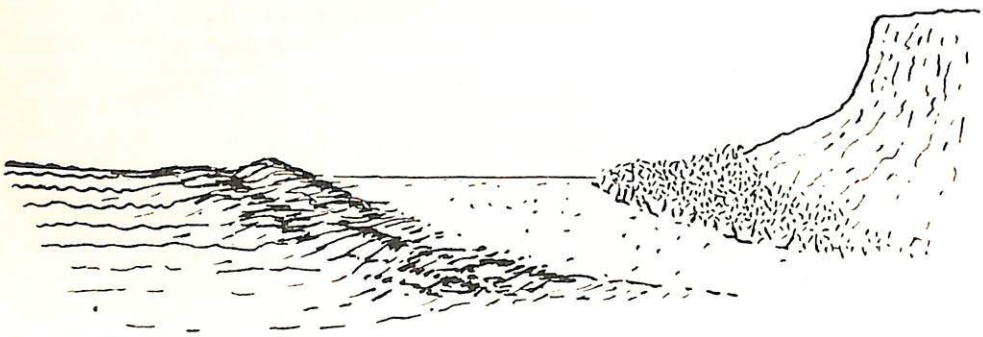


FIG. 135 (i).—Sea--no echo if smooth. Breakers—strong echoes. Sloping beach—poor echo. Vegetation—gives much scattering and returns fair echo. Sloping land—good echo. Bluff—very good echo.

A large vertical surface, such as a cliff, at right-angles to the direction of the pulse will have all points at the same range for all practical purposes and, the echo from each little area of the surface will arrive at the set at the same time making a large total echo strength and giving a big detection range. If the surface were to slope away from the set each little reflecting area would be at an increased range as their height extended and their echoes would not arrive at the set at the same time. Hence the sum total of power at a given instant would be small compared to that of a vertical surface of the same height. Sloping surfaces give a long echo which will get longer and weaker as the slope decreases. In general, the larger the target, the more it approaches a plane perpendicular to the pulse direction, the higher it is and the better conductor its material is the stronger its echo power. In the case of ships, the bigger and more broadside to the pulse they are the better will be the echo. Vessels with little or no superstructure and small freeboard give poor echoes.

Buoys, owing to their small size and height and poor shape, make bad targets, particularly the conical buoy. Pillar buoys, of greater height than the others, are more satisfactory.

Icebergs are usually good targets if they have vertical faces but when the berg presents a face which is smooth and sloping a specular reflection will occur and no echo returned to the aerial. Berg echoes can change much in strength as a vessel is passing them due to the changing aspect.

Growlers are dangerous because their low height and small size makes them a poor target whose detection range may be within the sea-clutter area thus making their detection difficult.

Sand banks and mudflats give an almost specular reflection therefore make poor targets which may not be detected until very close range. Seas breaking around them give good evidence of their presence. In rough water they would appear as dark patches in the clutter area.

Sand dunes, with their rougher nature and greater height are better than sand banks and sloping beaches but are not good enough for long range detection.

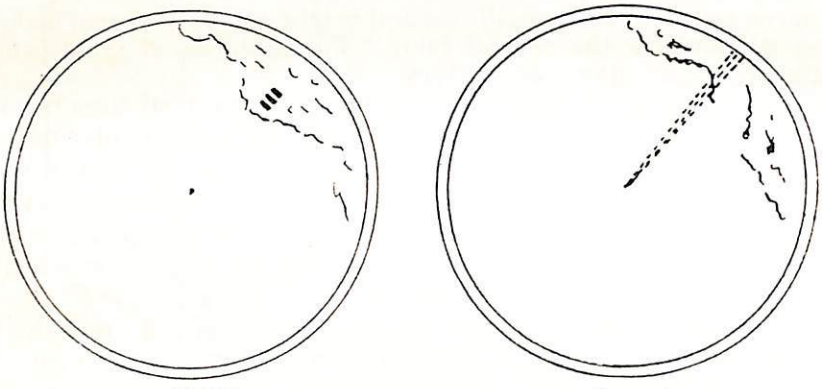
Built-up areas give very strong echoes due to the large number of plane vertical surfaces involved laying in random directions. Piers and sea walls also are good when lying at right angles to the pulse direction. Low height, however, prevents them being detected at long range. Circular section buildings with a taper in them are poor targets. This will apply to lighthouses, chimneys and steeples.

The identification of natural land targets is very difficult indeed unless visual checks can be made. High vertical cliffs are the least difficult but hilly country is almost impossible to identify due to the variety of heights, slopes and aspects. The individual hills may be radar conspicuous on one bearing but not so on another so that, as the ship moves along such a coast the picture on the P.P.I. constantly changes on the landward side of the coastline, sometimes very much indeed for a small change in ship's position. When using radar for navigation on a coast that is little known to the observer, the chart and directions should be consulted carefully to ascertain the nature of land to be dealt with and to assess the possible detection ranges of objects which are likely to be radar conspicuous. At

all times the tongue should be very much in the cheek and the cover off the sounding machine.

The best advantage from radar for navigation may be obtained by those who are on a regular run and take the opportunity of observing the radar picture in clear weather and checking their observations visually, then recording them for future reference.

173. Ramarks.—A ramark is a beacon which transmits continuously at frequencies in the radar band. When the ship's scanner faces the ramark the ramark transmission is picked up by the ship's receiver and is displayed as a narrow sector of broken dotted or dashed line radiating from centre to edge of the tube on the bearing of the ramark. Ramarks may be used to identify objects which are not otherwise radar conspicuous They give bearing only.



Racon. Ramark.

FIG. 136.

174. Racon.—This consists of a radar transmitter and receiver installed at some point it is required to identify. When the ship's scanner faces the Racon the ship's pulse is picked up by the Racon receiver, amplified and used to fire the Racon transmitter. The modulated (pulsed) Racon transmission arrives at the ship with its leading edge nearly coincident with the echo of the object and is displayed as shown. The number of Racon points will identify the object. The inside of the first Racon point will give range. Bearing is also given (see page 174).

175. Radar Fixing.—Methods in order of preference.

1. Radar range and visual bearing of an isolated object clear of land. For example, a lightship, beacon, or small island.

2. Radar ranges of several radar-conspicuous objects, which can be identified, used as position circles.

3. Radar range and bearing of an object.

The beam width causes distortion of the picture, as illustrated Fig. 137, because as soon as a target is within the beam it will return an echo which will be displayed on the bearing of the centre line of the beam. This

has the effect of broadening or extending points of land on a P.P.I. making bearings from the P.P.I. poor compared with visual bearings.

Ranging on the P.P.I. is very good, particularly if points are chosen where the pulse hits the coastline at right-angles, thus reducing the effect of beam width distortion to minimum.

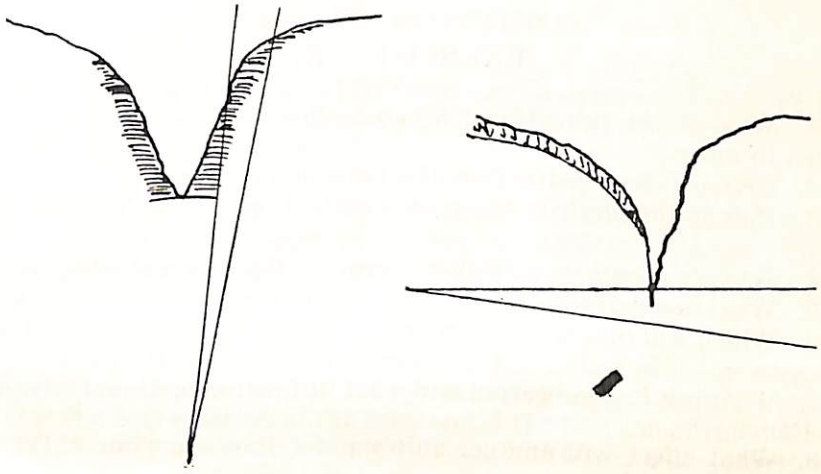


FIG. 137.—Distortion due to beam width.
Sides of point of land are extended on P.P.I. giving poor bearing, but good range of point may be obtained.
Land is extended to seaward giving poor bearing. Ship echo is also distorted.

176. The Radar Log.—This should be compiled to form a record of radar performance, detection ranges of various targets under different weather conditions, and pictorial record of land fall. Any particular benefit derived from the set and also its limitations should also be entered. Because the log is of benefit mainly, to the user of the radar, as a collection of previous experience only targets about which full information can be obtained should be entered, that is size, type, maximum detection, range, aspect, state of sea, whether light or loaded in the case of ship targets, area of use and the performance monitor reading. With land targets the name, bearing and approximate height, should be entered. Meteorological conditions affect the performance of the set and should always be entered when an observation is recorded.

177. Radar Reflectors.—These devices consist essentially of three flat triangles of metal, or other good reflecting material, arranged so they are mutually at right-angles to each other like the corner of a box (corner reflector). Each corner is a directive target and in order to obtain satisfactory all-round coverage the corners may be fitted in groups of five (pentagonal cluster) or an octahedral cluster may be formed by three metal plates intersecting each other at right-angles giving a reflector having eight separate corners.

Reflectors are used to increase the radar detection range of targets which have a poor echoing quality. Buoys are a particular instance. They may also be usefully employed in small wooden vessels, lifeboats,

etc. The echo strengths of reflectors are affected by height, size, type, and sea clutter, so that a definite figure for the increase of detection range cannot be given as a general statement. Reflectors are more fully discussed in "The Use of Radar at Sea." Another use for reflectors is to arrange buoys, fitted with them, in patterns for identification purposes.

EXERCISE XX.

1. What is the principle of range finding by echo, and how is this applied to radar ?
2. Describe the construction of a cathode ray tube.
3. How is the electron beam of a cathode ray tube focussed on the screen ?
4. What is meant by a shadow sector ? What is a shadow area ?
5. What is a performance monitor and how would you use it ?
6. Which will obscure most echoes, a funnel or crosstrees ? Explain your answer.
7. What is a Racon beacon, and what are its navigational advantages over Ramark ?
8. What effect will another ship's radar have on your P.P.I. ? Is this effect serious ?
9. Why do mountains show on a radar screen but not at the correct range ?
10. What do bearing discrimination and bearing accuracy depend on ? Illustrate your answer.
11. What is range discrimination ? What does it depend on ?
12. What is swept gain, and how is it adjusted ?
13. What is side lobe effect ? How does it affect the P.P.I. ?
14. Why is it necessary to plot echoes as they appear on the P.P.I. ?
15. What is the effect of lapse rate on radar echoes ?
16. If there is a long sloping beach, with a wooded foreground, and a range of hills inland how would this appear on the P.P.I. ?
17. What kind of radar results would you expect in N.E. trade wind area ?
18. What is super-refraction, and what effect will this have on target response ?
19. What are the probable effects of a temperature inversion on radar reception ?
20. What kind of objects are likely to be radar conspicuous, and which are likely to be radar inconspicuous ? List three in each category.
21. What is sea clutter ? How is it reduced and how can you tell when a correct setting is achieved ?
22. How could you determine if there was a shadow sector on your screen ?
23. What limits the minimum range and maximum range of a radar set ?
24. What is meant by "second trace" errors and how do these appear on the P.P.I. ?
25. What is a radar duct ?

CHAPTER XXI.

RADAR PLOTTING

178. Plotting Terms.—The following Glossary of Radar Plotting Terms has been issued by the Ministry of Transport as a guide to candidates for certificates (Notice No. M.357).

ASPECT.—The nearer angle between the other vessel's head and the line of sight. It is expressed in degrees (0—180) and qualified Red or Green according to whether the Port or Starboard side of the other vessel is open.

APPARENT MOTION.—Is represented by a line joining successive positions of an echo on the P.P.I. or a RELATIVE PLOT. If on a RELATIVE PLOT, O is the first position of the echo and A the position at the end of the PLOTTING INTERVAL, it is represented by the line OA and is symbolised by

BEARING.—The angle between own fore and aft line and the line of sight, or between the true meridian and the line of sight. If measured from own fore and aft line it is expressed in degrees (0—180) and qualified Red or Green according to whether on the port or starboard side. If measured from the true meridian it is expressed in degrees (000—359 T) clockwise. Any change of bearing is expressed as " Drawing forward " or " Drawing aft."

NEAREST APPROACH.—The least calculated distance to which two vessels will close if neither alters course or speed. It is expressed in miles or cables.

PLOTTING INTERVAL.—The time in minutes elapsing between the first and last readings of range and bearing of an echo which determine the length of the APPARENT MOTION line, OA.

PROPER MOTION.—The course steered and speed of own vessel or the other vessel during a PLOTTING INTERVAL as represented by the construction lines on the plotting diagram. If W is the ZERO SPEED POSITION on a RELATIVE PLOT the proper motions of own vessel and the other vessel are represented by WO and WA respectively, and are symbolised by

RELATIVE PLOT.—A plot based on a line joining successive positions of the echoes as shown on a P.P.I.

RANGE.—Distance to the target expressed in miles or cables. Any change of range is expressed as " increasing " or " decreasing."

TRUE PLOT.—A plot in which own ship's movement through the water is depicted to scale and the movement of the target is found by plotting its BEARING and RANGE at suitable intervals. It may be made either North up or ship's head up.

ZERO SPEED POSITION.—The anticipated position at the end of a plotting interval of the echo on the P.P.I. or plot of a target which is making no way through the water.

REPORTS

The reports from the plotter to the senior officer should contain, so far as it is known, the following information :—

(*a*) Bearing

(*b*) Range

(*c*) Nearest approach and time to elapse in minutes

(*d*) Aspect.

A first report giving bearing and range should be given as soon as an echo is seen on the P.P.I.

The second report would consist of new bearing and range qualified by any change since the first report together with nearest approach and time to elapse in minutes before nearest approach position is reached.

The full report after plotting would include aspect.

A typical full report might be as follows :—

" Vessel bearing Green 45 drawing forward, range 4 miles decreasing, aspect Red 50, nearest approach 1 mile in 8 minutes."

197. Plotting.—A P.P.I. shows a ship target as a point of light and the only direct information the radar will give regarding the target is its range and bearing. This, in itself, is insufficient information from which to draw any conclusions concerning risk of collision or the action to be taken should the risk exist. Certain conclusions may be arrived at by observation of a number of ranges and bearings of the same target taken at different times and, in order that these conclusions may be reached, some form of recording previous observations must be used. The most convenient form of recording would be that of marking the position of the target on the glass face of the P.P.I. with a pencil but, as yet, this is not a practical proposition. The next best thing is to mark our own ship on a piece of paper or Plotting diagram and then mark the position of the target in terms of range and bearing from our own position. This is called Radar Plotting and its use will be apparent in the examples which follow. There are two forms of Plot, Relative Plot and True Plot.

180. The Relative Plot.—A plot based on a line joining seccessive positions of the echoes as shown on a P.P.I.

In the Relative plot the target's movement is depicted relative to our own, that is considering our own ship to be stopped, just as it appears to be at the centre of the P.P.I. when all other objects will move with a velocity which will be a combination of our and their own.

* Vector—a line having two qualities (*a*) direction (*b*) magnitude. In the Plot it is used to depict velocity, that is, a particular speed made in a particular direction.

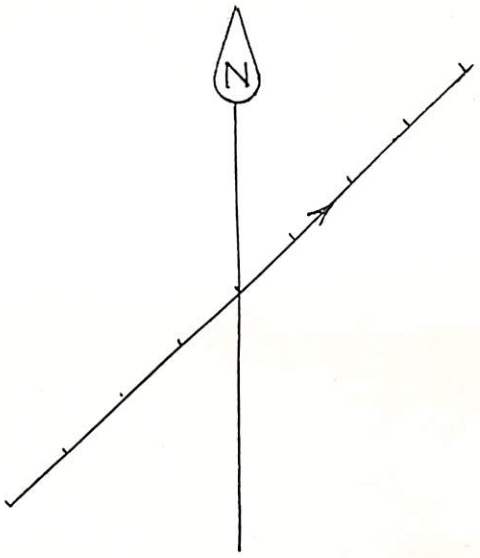


FIG. 138.

EXAMPLE.—A ship is steaming N.E. at 8 knots. A line drawn in a direction of N.E. and of a length 8 units to some suitable scale means the same thing.

The arrow only indicates direction and prevents this vector being S.W. 8 knots. In plotting, such vectors are used in a speed-vector triangle or the triangle of velocities.

Let us consider an object which has two velocities applied to it at one time, then it follows that, because it cannot move two ways at one time, it must move in some direction and at some speed which will be a resultant of these two velocities. For example, if a vessel has the echo of another vessel on her P.P.I. then that echo will appear to move with a velocity produced by the other ship's velocity and our own velocity. That velocity is called the Apparent Motion. If the echo of another vessel is plotted at regular intervals then the plot would appear as in Fig. 139, if both ships hold their course and speed.

XA, XB,—XG represent ranges and bearings as taken from the P.P.I. and plotted on paper from our vessel X. The line joining the points is the Apparent Motion of the other vessel. There are two important things which must not be overlooked when working problems on the relative plot.

* See "Munro's Mathematics for Deck Officers."

1. Our own ship does not, under any circumstances, leave the centre of the P.P.I., that is, the centre of the plot, in Fig. 139.

2. The target does not, under any circumstances leave the Apparent Motion even though the Apparent Motion changes as it will do if either ship alters course or speed.

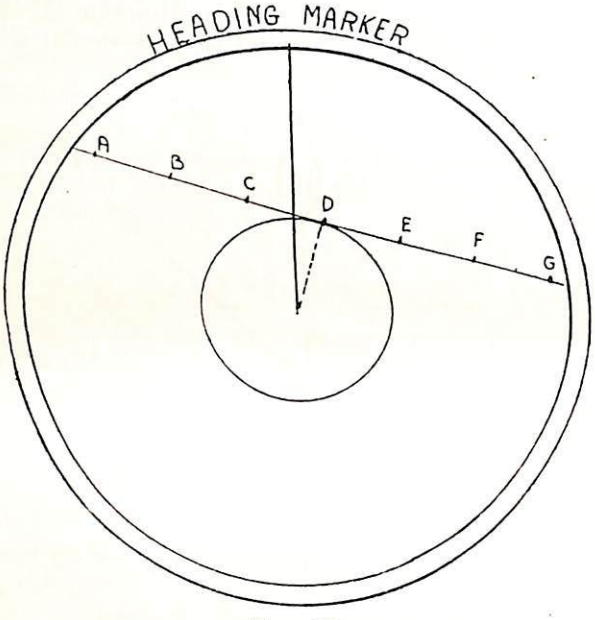


FIG. 139.

If the echo moves through points A, B, C, etc., then it is clear that the closest she will get to our own ship will be at position D, that is, the point where the apparent motion makes a tangent to the circle. The radius of this circle is called the Nearest Approach.

If the points A, B, and C are plotted at equal intervals of time and they fall on a straight line at equal intervals then we may assume that the other ship has maintained a steady course and speed. Two points would be insufficient because the other vessel may have altered course or speed or both during the interval. Four points would be more satisfactory in practice but three is usually considered to be sufficient. The echo is, then, at point C and we have assumed that she has a steady course and speed, so that the points D, E, etc. may be predicted, so also may be the nearest approach and the time of the nearest approach.

EXAMPLE.—A vessel sights another on her P.P.I., the bearings and ranges being as follows :—

Time.	*Bearing.*	*Range.*
0730	Green 30°	8 miles.
0736	Green 27°	6 miles.
0742	Green 20°	4 miles.

The bearings and ranges are plotted, they fall on a straight line and the time intervals are represented by equal divisions, so then, assuming her course and speed to be steady, the position of the echo can be predicted and the nearest approach obtained. The time of the nearest approach lies between the times 0748 and 0754 and would be estimated as 0752 which is accurate enough for all practical purposes.

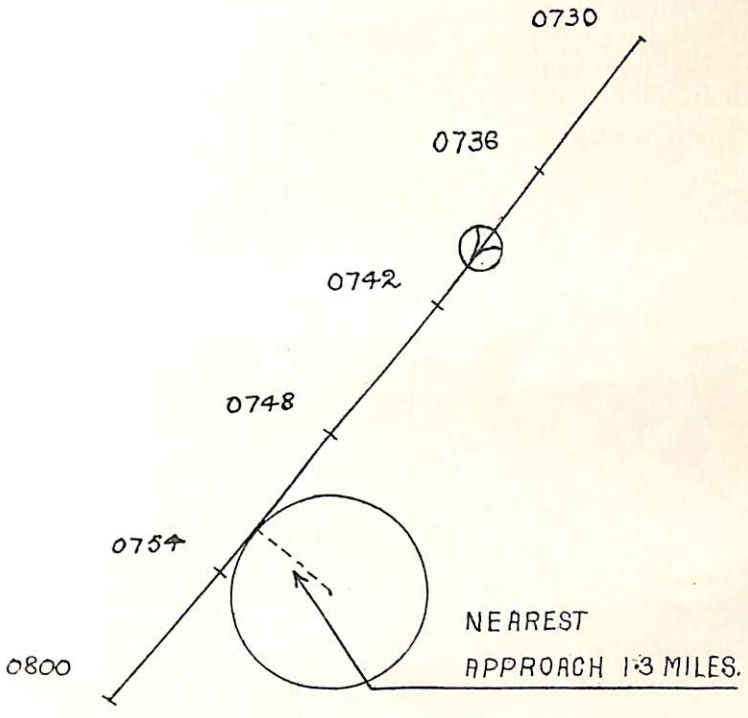


FIG. 140.

The interval between 0730 and 0742 (that is now) is called the Plotting Interval. From 0742 onwards is prediction and the advantage of it is that if, at say 0748, the echo is not at the predicted point then we are warned that the other vessel has altered course or speed or both.

For the remainder of our discussion of problems we will assume that the other vessel is keeping a steady course and speed and use only the first point and the last point of the plotting period.

The scale used in working the examples was 1 cm. = 1 mile and the answers obtained by measurement.

The Triangle of Velocities.—Suppose we forget radar for the moment and consider the following problem.

Ship B, steaming 050° at 8 knots. Ship A steaming 350° at 12 knots and bearing 110° distant 5 miles from B. Find which will pass ahead, by how much, in what time, their nearest approach and the time to nearest approach.

Fig. 141 (a) sets out the problem in vector form. If we consider ship B to be stopped then ship A will appear to move with two velocities, her own and ship B's. By applying both these velocities to ship A, as shown in Fig. 141 (b), the apparent velocity will be obtained. Set off A's velocity and B's velocity from a point W and join the other ends of these vectors, points O and A, to obtain the apparent velocity O A. Now, in Fig. 141 (a) ship B is stopped then A will be the only one moving and she will move with the apparent velocity found in Fig. 141 (b). By transferring this apparent velocity to Fig. 141 (a) and setting it off from ship A we may determine that (*a*) A will pass ahead of B, (*b*) by 1·6 miles (BX), (*c*) nearest approach 1·7 miles (BY), (*d*) in 27½ minutes (AY).

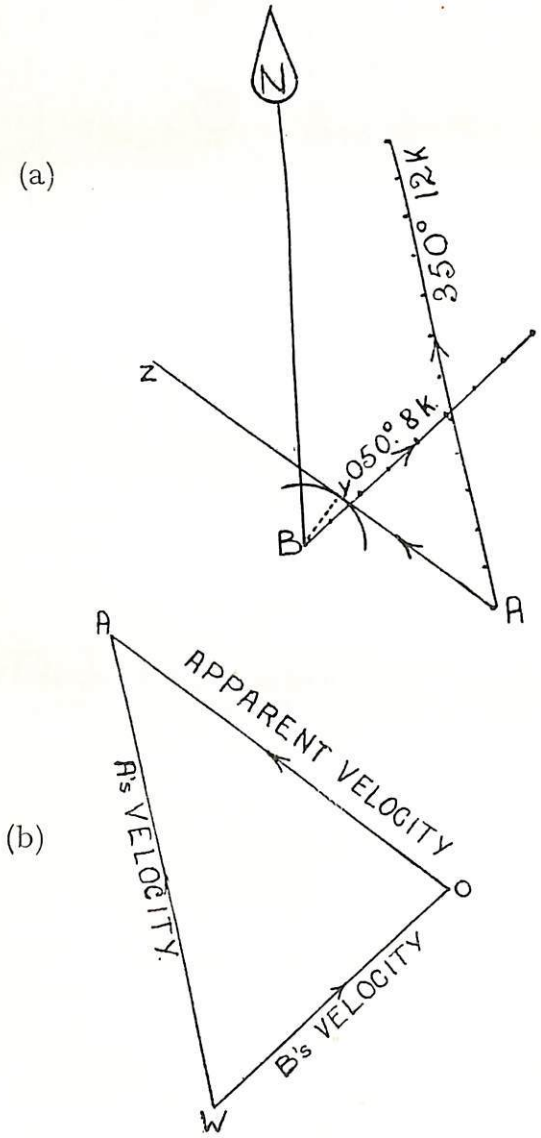


FIG. 141.

In the last problem we were given the courses and speeds of both ships which, of course, a radar will not give us directly but by plotting both ranges and bearings we do obtain the Apparent Motion from which the other particulars may be deduced.

EXAMPLE.—Ship A steaming 300° at 9 knots sights another on her P.P.I. bearing Red 40° (260° T) range 9 miles, 20 minutes later it bore Red 10° (290° T) range 5 miles. Find Nearest Approach, time to Nearest Approach, B's aspect (aspect is the angle between other ship's head and line of sight), B's course and B's speed.

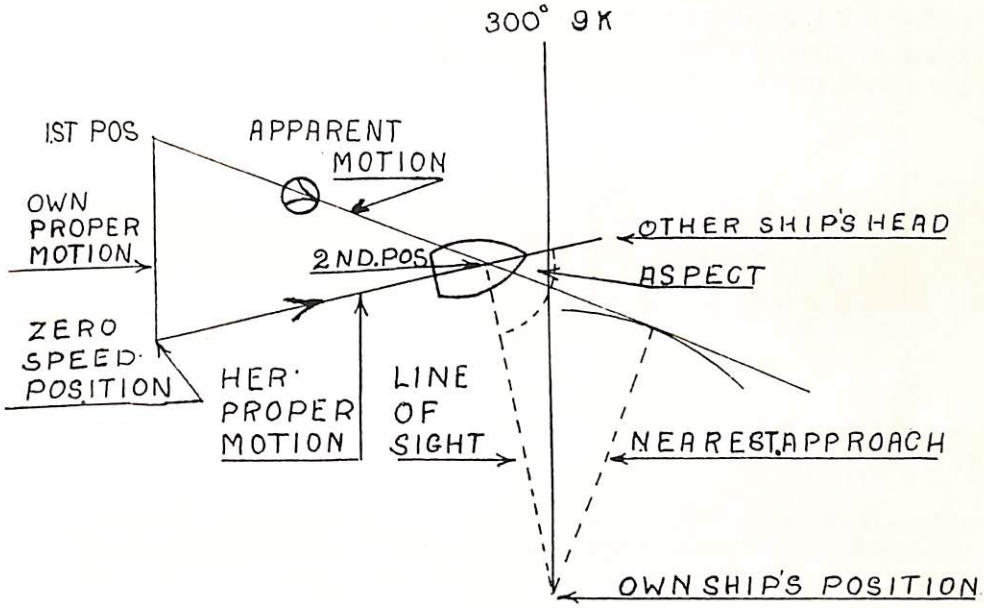


FIG. 142.

In Fig. 142

1. Lay off heading marker, the end is own ship's position.

2. Lay off first range and bearing.

3. Lay off second range and bearing.

4. Lay off Apparent Motion through these points and continue it.

5. Lay off Own Proper Motion always from first position and always downwards, parallel to the heading marker.

6. Join end of own proper motion to the second position to get her Proper Motion.

Note that because the apparent motion is for 20 minutes that the two proper motions must also be for 20 minutes.

The Plotting Interval is 20 minutes. Compare the distance from second position to the point of nearest approach with the length of the plotting interval to obtain time of nearest approach.

The angle at the zero speed position between own proper motion and her proper motion is the difference between own ship's course and other ship's course. In this case, 77° to starboard of ours or 017° T.

Her speed is the length of her proper motion multiplied by three since her proper motion is for 20 minutes.

WORKED EXAMPLE 1.—Ship A steaming 200° at 9 knots sights another on her P.P.I. bearing Green 40° range 8 miles and after 20 minutes it bore Green 20° range 4 miles. Find nearest approach, time to nearest approach, her aspect, course and speed.

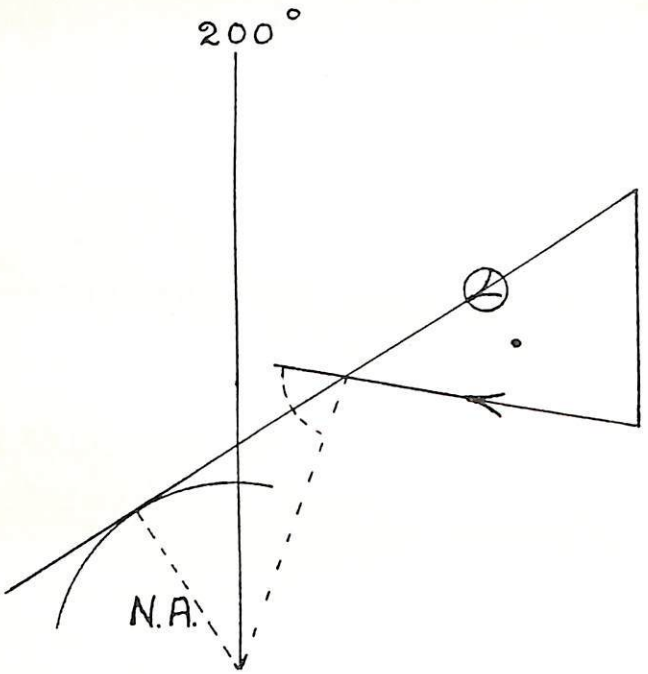


FIG. 143.—Example 1.

Nearest approach 2·5 miles. Time to N.A. 14 mins.
Aspect Red 80°. Course 120°. Speed 11·5 knots.

WORKED EXAMPLE 2.—Ship A steaming 130° at 8 knots sights another on her P.P.I. bearing Red 30° range 8 miles. After steaming 60 minutes it bore Red 60° range 4·6 miles. Find N.A., time to N.A., her aspect, course and speed.

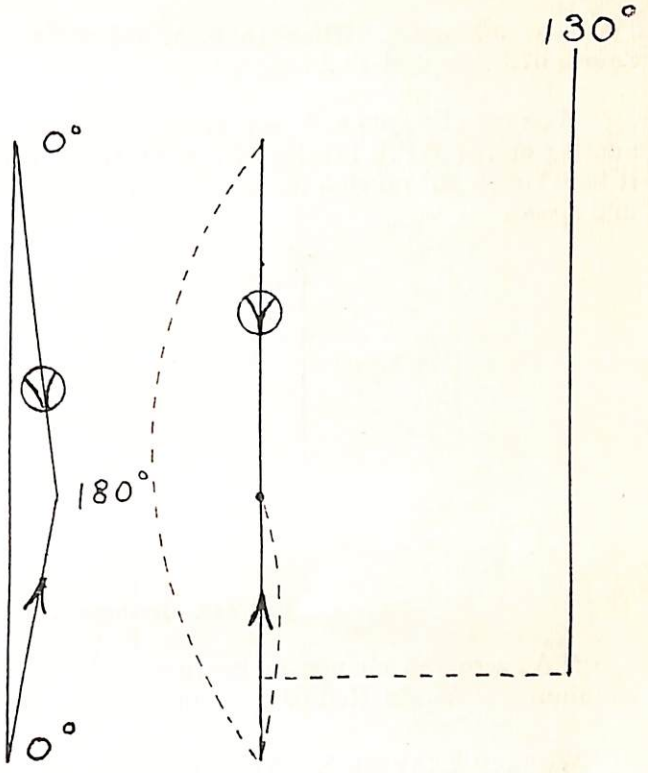


FIG. 144.—Example 2.

The target is on a parrallel course and is being overtaken. The triangle has one angle of 180° and two of zero making it a straight line. It may be better understood by opening the triangle up a little as shown.

N.A. 4 miles. Time to N.A. 30 minutes. Aspect Green 120°. Course 130°. Speed 3·4 knots.

WORKED EXAMPLE 3.—A vessel steaming 250° at 8 knots sights another on her P.P.I. bearing Green 20° range 9 miles. After 15 minutes it bore Green 50° range 4·1 miles. Find N.A., time to N.A., her aspect, course and speed.

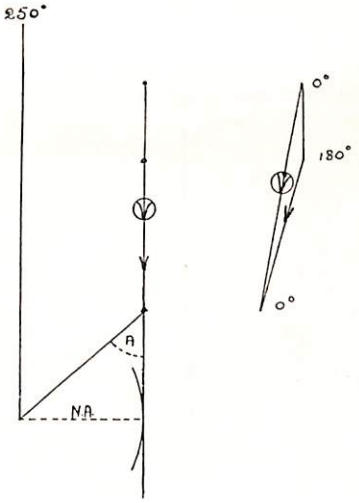


FIG. 145.—Example 3.

N.A. 3·1 miles. Time to N.A. 6·7 minutes. Aspect Green 50°. Course 070°. Speed 15·2 knots.

WORKED EXAMPLE 4.—A vessel steaming 110° at 9 knots sights another on her P.P.I. bearing Green 80° range 7 miles. After 20 minutes it bore Green 80° range 5 miles. Find N.A., time to N.A., aspect, course and speed.

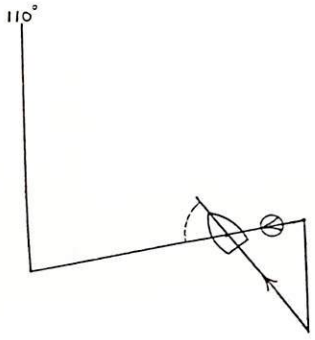


FIG. 146.—Example 4.

N.A. zero (no change in bearing—collision course). Time to N.A. 50 minutes. Aspect Red 63°. Course 073°. Speed 9·9 knots.

WORKED EXAMPLE 5.—A ship steaming 040° at 6 knots sights another on her P.P.I. bearing Red 160° 8 miles. After 30 minutes it bore Red 150° range 5·6 miles. Find N.A., time to N.A., aspect, course and speed.

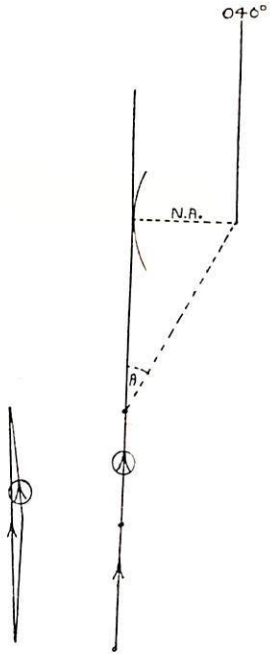


FIG. 147—Example 5.

N.A. 2·75 miles. Time to N.A. 56·5 minutes. Aspect Green 30°. Course 040°. Speed 11·2 knots.

WORKED EXAMPLE 6.—A vessel steaming 120° at 6 knots sights a lightship bearing Red 30° range 8 miles and after 1 hour it bore Red 70° range 5·5 miles. Find the set and drift.

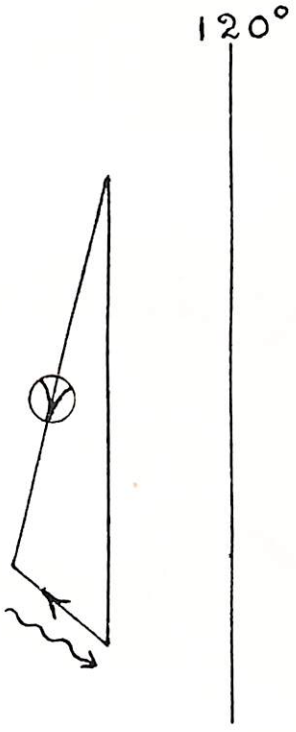


FIG. 148.—Example 6.
Because plot is relative, set is always shown reversed.

Set 250°. Drift 1·5 miles.

WORKED EXAMPLE 7.—A vessel steaming 120° at 9 knots sights another on her P.P.I. bearing Green 30° range 8 miles and after 20 minutes it bore Green 25° range 6 miles. Find the course to steer so that the nearest approach is 3 miles, also the time to nearest approach.

There are six factors in the triangle of velocities, three directions and three magnitudes and the Apparent Motion depends upon four of these, her direction and speed and our direction and speed. Alter any one of these four and the apparent motion will alter. If her proper motion is

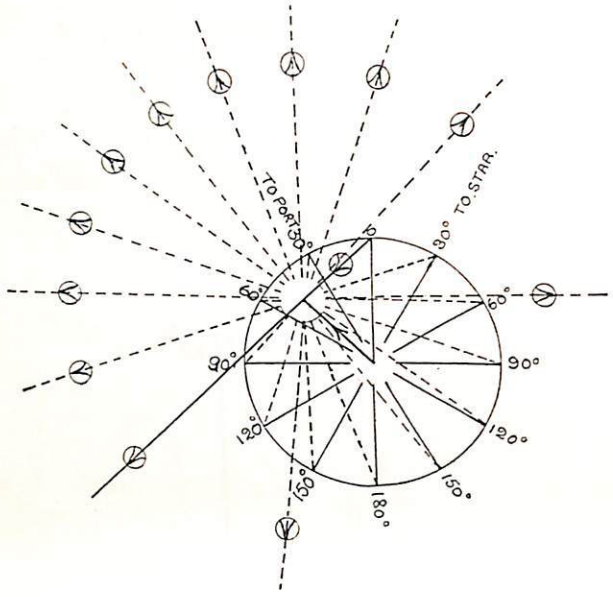


FIG. 149.

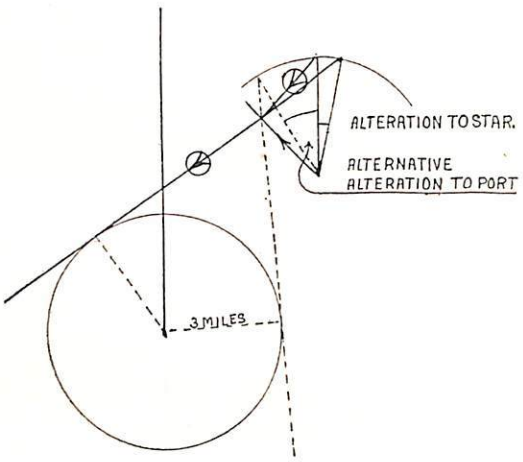


FIG. 150.—Example 7.

constant then any alteration of our course only will affect the apparent motion as shown in Fig. 149.

Work the problem to find her proper motion as shown in Worked Example 1 then

1. Draw a circle round own ship of radius 3 miles, the nearest approach.

2. Draw an arc of a circle of radius " our proper motion " with centre of zero speed position.

3. Draw the new apparent motion from where the ship is now (2nd position) and as a tangent to the circle of nearest approach then extend it until it cuts the " own proper motion " circle.

4. Join the point mentioned in Step 3 to zero speed position and this will be our new proper motion. The difference in angle between this and the original proper motion will be the alteration of course required.

Alter 11° to starboard 131° or
Alter 30° to port 090°.

WORKED EXAMPLE 8.—A vessel is steaming 200° at 8 knots.

Time.	*Bearing.*	*Range.*
1230	Green 40°	8 miles.
1242	Green 40°	5 miles.
1248	Course altered to 250°.	

Find the N.A. and time of N.A.

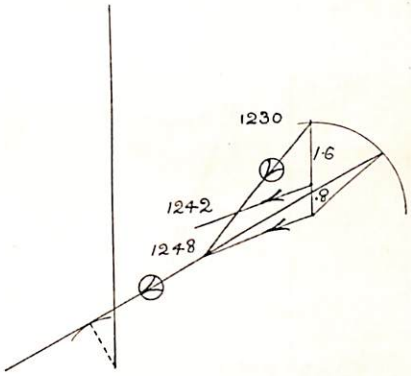


FIG. 151.—Example 8.

N.A. 1·3 miles. Time of N.A. 1259.

WORKED EXAMPLE 9.—A vessel steaming 140° at 10 knots sights another on her P.P.I. bearing Red 50° range 9 miles. After 24 minutes she bore Red 50° range 7 miles. Find the reduction of speed so that the

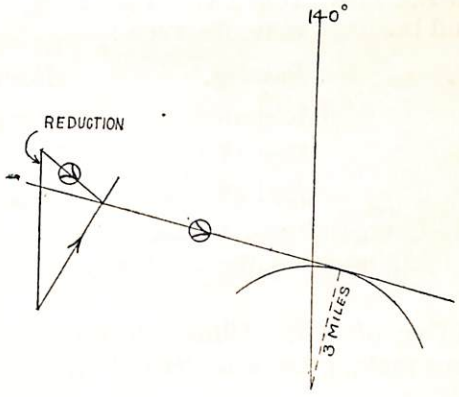


FIG. 152.—Example 9.

nearest approach is 3 miles assuming that the reduction is immediately effective.

Note that in this case only the length, not the direction, of our proper motion changes.

Reduce speed by 2·25 knots.

WORKED EXAMPLE 10.—A vessel steaming 300° at 8 knots sights another on her P.P.I. bearing Green 10° range 8 miles and after 18 minutes it bore Green 20° range 6 miles. The speed was then reduced to 5 knots. Find the nearest approach and the time to N.A. assuming the alteration to be immediately effective.

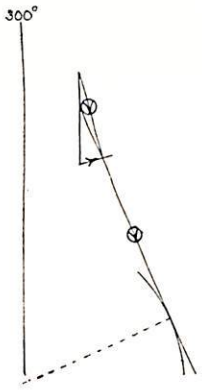


FIG. 153.—Example 10.

N.A. 4·4 miles. Time to N.A. 50 minutes.

WORKED EXAMPLE 11.—From a vessel steaming 300° at 9·5 knots the following ranges and bearings were observed :—

Time.	*Bearing.*	*Range.*
1500	Red 43°	7·5 miles.
1506	Red 41°	6·3 miles.
1512	Red 38°	5·2 miles.
1518	Course altered to 250°, the vessel taking 4 minutes to steady.	

Find N.A. and time of N.A. Allow half of the steadying time on old apparent motion thus making the **effective** alteration time 1520 hours.

N.A. 2·7 miles at 1529 hours.

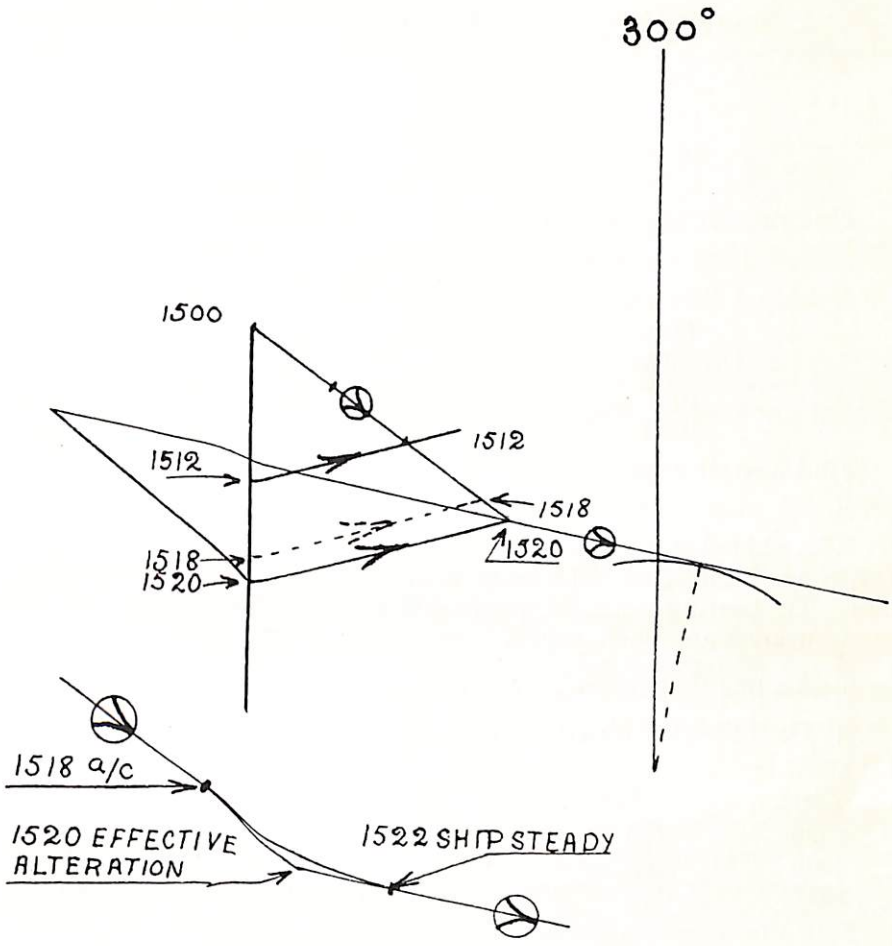


FIG. 154.—Example 11.

EXERCISE XXI.

1. A ship steaming 253° at 9 knots sights another on her P.P.I. bearing Green 47° range 8·5 miles. After 6 minutes she bore Green 40° range 7·6 miles and after a further 6 minutes she bore Green 30° range 7 miles. Find nearest approach, time to nearest approach, aspect, course and speed.

2. A ship steaming 010° at 8 knots sights another on her P.P.I. bearing Red 75° range 7·4 miles. After 3 minutes it bore Red 69½° range 6·8 miles and after a further 3 minutes it bore Red 63° range 6·3 miles. Find nearest approach, time to nearest approach, aspect, course and speed.

3. A ship steaming 253° at 12 knots observes the following bearings and ranges :—

Time.	*Bearing.*	*Range.*
1530	265° T	8 miles.
1533	267° T	7 miles.
1536	269½° T	6 miles.

Find nearest approach, time of nearest approach, aspect, course and speed.

4. Ship A steaming 270° at 6 knots makes the following observations :

Time.	*Bearing.*	*Range.*
1015	Red 105°	6 miles.
1027	Red 90°	5·75 miles.
1039	Red 75°	6 miles.

Find nearest approach, time of nearest approach, aspect, course and speed.

5. A ship steaming 150° at 8 knots sights another on her P.P.I. at 0712, range 6 miles, at 0718 range 5 miles and at 0724 the range was 4 miles. The bearing remained steady at Green 10°. Find nearest approach, time to nearest approach, aspect, course, and speed.

6. Assume that the echo in No. 5 were a lightship, find set and drift.

7. The following observations were made by a vessel steaming 100° at 8 knots :—

Time.	*Ship A.*	*Ship B.*	*Ship C.*
2000	Red 42° 5′	Red 60° 7′	Green 45° 9′
2006	Red 42° 4′	Red 54° 6′·5	Green 42° 8′
2012	Red 42° 3′	Red 47° 6′·2	Green 39° 7′·2

Find the nearest approach, time of nearest approach, aspect, course, and speed for each vessel.

8. The following echoes were observed on the P.P.I. of a vessel steaming 000° at 10 knots :—

Time.	*A.*	*B.*	*C.*
1300	Green 10° 9′	Green 37° 8′	Red 12° 8′
1312	Green 4½° 6′·4	Green 45° 6′·4	Red 6° 7′·8
1324	Red 9° 4′	Green 57° 5′	Red 0° 7′·8

Find the nearest approach, time of nearest approach, aspect, course, and speed. If B is a lightship find also set and drift.

9. Your vessel is steering 270° at 6 knots. The following is a record of echoes on the P.P.I. from three vessels :—

Time.	*A.*	*B.*	*C.*
1505	Green 20° 6′	Green 100° 3′	Red 10° 5′
1510	Green 18° 4′·9	Green 90° 2′·9	Red 10° 4′·2
1515	Green 14° 3′·9	Green 80° 3′	Red 10° 3′·4

Find nearest approach, time of nearest approach, aspect, course, and speed of each vessel.

10. Your vessel is steering 090° at 9 knots. The following is a record of echoes on the P.P.I. from two vessels on the portside and a lighthouse on the starboard side :—

Time.	*A.*	*B.*	*C.*
0410	Green 14° 5′	Red 4° 5′	Red 19° 2′·4
0415	Green 21° 4′·2	Red 6° 3′·7	Red 17½° 2′·7
0420	Green 31° 3′·4	Red 8° 2′·5	Red 16° 3′

Find nearest approach, time of nearest approach, aspect, course, and speed of the two vessels also the set and drift.

11. Ship A steaming 200° at 7 knots sights ship B on her P.P.I. bearing Red 40° range 8′·5 miles, 12 minutes later she bore Red 43° range 7 miles. The course was then altered to 140°. Find nearest approach and time of nearest approach.

12. Ship A steaming 100° at 6·5 knots sights ship B on her P.P.I. bearing Green 130° range 6 miles, after 24 minutes she bore Green 100° range 4·5 miles. The course was then altered 30° to port. Find nearest approach and time to nearest approach.

13. A vessel steaming 300° at 9 knots sights another on her P.P.I. bearing Red 40° range 9 miles. After steaming 30 minutes it bore Red 35° 5 miles. The course was then altered to 270°. Find nearest approach and time to nearest approach.

14. A vessel steaming 153° at 8 knots sights another on her P.P.I. bearing 0° range 8 miles and after 12 minutes it bore 0° range 4·5 miles. The course was then altered to 183° for 6 minutes when the course of 153° was resumed. Find nearest approach and time to nearest approach.

15. A vessel steaming 027° at 9 knots sights another on her P.P.I. bearing Green 50° range 7 miles and after 20 minutes it bore Green 50° 5 miles. Find the course to steer so that the vessel will have a nearest approach of 2 miles.

16. A vessel steaming 125° at 8 knots sights another on her P.P.I. bearing Red 90° range 6 miles and after 1 hour she bore Red 90° range 4 miles. Find the course to steer so that the nearest approach is 2 miles.

17. A vessel is steaming 350° at 6 knots and sights another on her P.P.I. bearing Red 5° range 8 miles. 12 minutes later she bore Red 7° range 6 miles. Find the alteration to starboard required so that the nearest approach is 2 miles.

18. A vessel is steaming 300° at 5 knots and sights another on her P.P.I. bearing Green 43° range 5 miles and after 12 minutes she bore Green 37° range 3·2 miles. Find course to steer so that the nearest approach is 2 miles.

19. A vessel is steaming 270° at 10 knots and makes the following observations :—

Time.	*Bearing.*	*Range.*
0030	Red 42°	7'·8 miles
0036	Red 40°	7'·2 miles
0042	Red 38°	6'·6 miles

0047 Course altered to 220° the vessel taking 2 minutes tosteady. Find nearest approach and time of nearest approach.

20. A vessel steaming 180° at 8 knots sights another on her P.P.I. bearing Green 65° range 9 miles and after 24 minutes she bore Green 65° range 7 miles, the course was then altered to 270° for 12 minutes before the course of 180° was resumed. Find nearest approach and time to nearest approach.

21. A vessel steaming 200° at 10 knots sights another on her P.P.I. bearing Green 30° range 8 miles, after 18 minutes it bore Green 30° range 6 miles. The speed was then reduced to 6 knots. Find the nearest approach assuming the alteration to b immediately effective.

22. A vessel steaming 100° at 9 knots sights another on her P.P.I. bearing Red 50° range 7·4 miles, 12 minutes later she bore Red 55° range 5 miles. Find the reduction in speed required so that the nearest approach is 2 miles, assuming that the reduction is instantaneous.

Experimental Racon at Bar Light-Vessel.—This is designed to give to the navigator, whose ship is radar-equipped, his range and bearing from the point at which the beacon is located. He should receive this information initially at horizon distance, although the light-vessel itself would not normally be visible on the radar screen at this range. The Racon flash is a greatly lengthened and reinforced echo, appearing as a bright line on the bearing of the light-vessel and extending from a point a few hundred yards beyond the position of the light-vessel to the circumference of the display.

Range can be measured to the point at which the Racon flash begins, which will normally be several hundred yards longer than the true range. The exact distance can be measured as soon as the light-vessel itself comes within radar range.

ANSWERS TO PLOTTING PROBLEMS

1.	NA 6′·4	in 13 mins.	Aspect R. 97°	Course 200°	Speed 17 knots
2.	NA 5′·3	in 10½ mins.	Aspect G. 75°	Course 051°	Speed 23½ knots
3.	NA 1′·7	in 16½ mins.	Aspect G. 17°	Course 173°	Speed 8½ knots
4.	NA 5′·75	at 1027	Aspect G. 105°	Course 270°	Speed 14 knots
5.	NA Zero	at 0748	Aspect R. 036°	Course 015°	Speed 2·5 knots
6.		Set 195°	Drift 0′·5		
7.	*A*. NA Zero	at 2030	Aspect G. 53°	Course 186°	Speed 7 knots
	B. NA 5′·7	at 2029	Aspect G. 100°	Course 134°	Speed 14 knots
	C. NA 3′·4	at 2050	Aspect R. 77°	Course 035°	Speed 10 knots
8.	*A*. NA 2′·2	at 1339	Aspect R. 77°	Course 248°	Speed 7 knots
	B. NA 3′·7	at 1346	...	...	...
	C. NA 7′·8	at 1327	Aspect R. 157°	Course 024°	Speed 10·75 knots
		Set 241°	Drift 0′·7		
9.	*A*. NA 1′·1	at 1532½	Aspect R. 40°	Course 144°	Speed 8·4 knots
	B. NA 2′·9	at 1510	Aspect R. 100°	Course 270°	Speed 12 knots
	C. Zero	at 1536	Aspect G. 22°	Course 059°	Speed 3·6 knots
10.	*A*. NA 2′·3	at 0431½	Aspect	Course	Speed
	B. NA 0′·3	at 0429	Aspect R. 7°	Course 270°	Speed 6 knots
	C. NA Past	...	Aspect G. 165°	Course 088°	Speed 12·6 knots
		Set 036°	Drift 0·7		

11. NA 3′ in 36½ mins.
12. NA 4′·5 at time of 2nd bearing
13. NA 2′·6 in 23½ mins.
14. NA 0′·45 in 15½ mins.
15. Alter Course 30° to Starboard (057°) or 20° to Port (007°)
16. Alter 72° to Port or 21° or 40° to Starboard
17. Alter 20° to Starboard
18. NA 5.0 m. at 0102 hrs.
19. Red 38° 6′·5
20. NA 2 m.
21. NA 3′·0
22. Reduce by 8 knots to 1 knot

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N.B.—This index gives paragraph numbers not page numbers.

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Dist.	STEAMING TIME					Dist.	STEAMING TIME				
	23	23½	24	24½	25		23	23½	24	24½	25
100	4·35	4·26	4·17	4·08	4·00	150	6·52	6·38	6·25	6·12	6·00
101	4·39	4·30	4·21	4·12	4·04	151	6·56	6·42	6·29	6·16	6·04
102	4·43	4·34	4·25	4·16	4·08	152	6·61	6·46	6·33	6·20	6·08
103	4·48	4·38	4·29	4·20	4·12	153	6·65	6·51	6·375	6·24	6·12
104	4·52	4·42	4·33	4·24	4·16	154	6·70	6·55	6·42	6·29	6·16
105	4·56	4·46	4·375	4·29	4·20	155	6·74	6·59	6·46	6·33	6·20
106	4·61	4·51	4·42	4·33	4·24	156	6·78	6·64	6·50	6·37	6·24
107	4·65	4·55	4·46	4·37	4·28	157	6·83	6·68	6·54	6·41	6·28
108	4·70	4·59	4·50	4·41	4·32	158	6·87	6·72	6·58	6·45	6·32
109	4·74	4·64	4·54	4·45	4·36	159	6·91	6·76	6·625	6·49	6·36
110	4·78	4·68	4·58	4·49	4·40	160	6·96	6·81	6·67	6·53	6·40
111	4·83	4·72	4·625	4·53	4·44	161	7·00	6·85	6·71	6·57	6·44
112	4·87	4·76	4·67	4·57	4·48	162	7·04	6·89	6·75	6·61	6·48
113	4·91	4·81	4·71	4·61	4·52	163	7·09	6·94	6·79	6·65	6·52
114	4·96	4·85	4·75	4·65	4·56	164	7·13	6·98	6·83	6·69	6·56
115	5·00	4·89	4·79	4·69	4·60	165	7·17	7·02	6·875	6·73	6·60
116	5·04	4·94	4·83	4·73	4·64	166	7·22	7·06	6·92	6·78	6·64
117	5·09	4·98	4·875	4·78	4·68	167	7·26	7·11	6·96	6·82	6·68
118	5·13	5·02	4·92	4·82	4·72	168	7·38	7·15	7·00	6·86	6·72
119	5·17	5·06	4·96	4·86	4·76	169	7·35	7·19	7·04	6·90	6·76
120	5·22	5·11	5·00	4·90	4·80	170	7·39	7·23	7·08	6·94	6·80
121	5·26	5·15	5·04	4·94	4·84	171	7·43	7·28	7·125	6·98	6·84
122	5·30	5·19	5·08	4·98	4·88	172	7·48	7·32	7·17	7·02	6·88
123	5·35	5·23	5·125	5·02	4·92	173	7·52	7·36	7·21	7·06	6·92
124	5·39	5·28	5·17	5·06	4·96	174	7·56	7·40	7·25	7·10	6·96
125	5·43	5·32	5·21	5·10	5·00	175	7·61	7·44	7·29	7·14	7·00
126	5·48	5·36	5·25	5·14	5·04	176	7·65	7·49	7·33	7·18	7·04
127	5·52	5·40	5·29	5·18	5·08	177	7·70	7·53	7·375	7·22	7·08
128	5·56	5·44	5·33	5·22	5·12	178	7·74	7·57	7·42	7·27	7·12
129	5·61	5·49	5·375	5·27	5·16	179	7·78	7·61	7·46	7·31	7·16
130	5·65	5·53	5·42	5·31	5·20	180	7·83	7·65	7·50	7·35	7·20
131	5·70	5·57	5·46	5·35	5·24	181	7·87	7·70	7·54	7·39	7·24
132	5·74	5·61	5·50	5·39	5·28	182	7·91	7·74	7·58	7·43	7·28
133	5·78	5·65	5·54	5·43	5·32	183	7·96	7·79	7·625	7·47	7·32
134	5·83	5·70	5·58	5·47	5·36	184	8·00	7·83	7·67	7·51	7·36
135	5·87	5·74	5·625	5·51	5·40	185	8·04	7·87	7·71	7·55	7·40
136	5·91	5·79	5·67	5·55	5·44	186	8·09	7·91	7·75	7·59	7·44
137	5·96	5·83	5·71	5·59	5·48	187	8·13	7·95	7·79	7·63	7·48
138	6·00	5·87	5·75	5·63	5·52	188	8·17	8·00	7·83	7·67	7·52
139	6·04	5·91	5·79	5·67	5·56	189	8·22	8·04	7·875	7·71	7·56
140	6·09	5·95	5·83	5·71	5·60	190	8·26	8·09	7·92	7·76	7·60
141	6·13	6·00	5·875	5·76	5·64	191	8·30	8·13	7·96	7·80	7·64
142	6·17	6·04	5·92	5·80	5·68	192	8·35	8·17	8·00	7·84	7·68
143	6·22	6·09	5·96	5·84	5·72	193	8·39	8·21	8·04	7·88	7·72
144	6·26	6·13	6·00	5·88	5·76	194	8·43	8·26	8·08	7·92	7·76
145	6·30	6·17	6·04	5·92	5·80	195	8·48	8·30	8·125	7·96	7·80
146	6·35	6·21	6·08	5·96	5·84	196	8·52	8·34	8·17	8·00	7·84
147	6·39	6·26	6·125	6·00	5·88	197	8·56	8·38	8·21	8·04	7·88
148	6·43	6·30	6·17	6·04	5·92	198	8·61	8·42	8·25	8·08	7·92
149	6·48	6·34	6·21	6·08	5·96	199	8·65	8·46	8·29	8·12	7·96
150	6·52	6·38	6·25	6·12	6·00	200	8·70	8·51	8·33	8·16	8·00

RATE OF CHANGE OF ALTITUDE PER MINUTE OF TIME

Azimuth	LATITUDE.												Azimuth
	42° 0′	42° 30′	43° 0′	43° 30′	44° 0′	44° 30′	45° 0′	45° 30′	46° 0′	46° 30′	47° 0′	47° 30′	
0° 30′	·097	·097	·096	·095	·094	·094	·092	·092	·091	·090	·089	·088	0° 30′
1 0	·194	·193	·192	·190	·188	·187	·185	·184	·182	·180	·179	·177	1 0
30	·292	·290	·287	·285	·283	·280	·278	·275	·273	·270	·268	·265	30
2 0	·389	·386	·383	·380	·377	·373	·370	·367	·364	·360	·357	·354	2 0
30	·486	·482	·479	·475	·471	·467	·463	·459	·455	·450	·446	·442	30
3 0	·583	·579	·574	·569	·565	·560	·555	·550	·545	·540	·535	·530	3 0
30	·681	·675	·670	·664	·659	·653	·648	·642	·636	·630	·625	·619	30
4 0	·778	·771	·765	·759	·753	·746	·740	·733	·727	·720	·714	·707	4 0
30	·875	·868	·861	·854	·847	·839	·832	·825	·818	·810	·803	·795	30
5 0	·972	·964	·956	·948	·940	·933	·924	·916	·908	·900	·892	·883	5 0
30	1·068	1·060	1·051	1·043	1·034	1·025	1·017	1·008	·999	·990	·981	·971	30
6 0	1·165	1·156	1·147	1·137	1·128	1·118	1·109	1·099	1·089	1·079	1·069	1·059	6 0
30	1·262	1·252	1·242	1·232	1·221	1·211	1·201	1·190	1·180	1·169	1·158	1·147	30
7 0	1·358	1·348	1·337	1·326	1·315	1·304	1·293	1·281	1·270	1·258	1·247	1·235	7 0
30	1·455	1·444	1·432	1·420	1·408	1·396	1·384	1·372	1·360	1·348	1·335	1·323	30
8 0	1·551	1·539	1·527	1·514	1·502	1·489	1·476	1·463	1·450	1·437	1·424	1·410	8 0
30	1·648	1·635	1·622	1·608	1·595	1·581	1·568	1·554	1·540	1·526	1·512	1·498	30
9 0	1·744	1·730	1·716	1·702	1·688	1·674	1·659	1·645	1·630	1·615	1·600	1·585	9 0
30	1·840	1·825	1·811	1·796	1·781	1·766	1·751	1·735	1·720	1·704	1·688	1·673	30
10 0	1·936	1·920	1·905	1·889	1·874	1·858	1·842	1·826	1·809	1·793	1·776	1·760	10 0

Azimuth	LATITUDE.												Azimuth
	48° 0′	48° 30′	49° 0′	49° 30′	50° 0′	50° 30′	51° 0′	51° 30′	52° 0′	52° 30′	53° 0′	53° 30′	
0° 30′	·088	·087	·086	·085	·084	·083	·082	·081	·081	·080	·079	·078	0° 30′
1 0	·175	·174	·172	·170	·168	·167	·165	·163	·161	·159	·158	·156	1 0
30	·263	·260	·258	·255	·252	·250	·247	·244	·242	·239	·236	·234	30
2 0	·350	·347	·343	·340	·337	·333	·329	·326	·322	·319	·315	·311	2 0
30	·438	·434	·429	·425	·421	·416	·412	·407	·403	·398	·394	·389	30
3 0	·525	·520	·515	·510	·505	·499	·494	·489	·483	·478	·472	·467	3 0
30	·613	·607	·601	·595	·589	·583	·576	·570	·564	·558	·551	·545	30
4 0	·700	·693	·687	·680	·673	·666	·659	·651	·644	·637	·630	·622	4 0
30	·788	·780	·772	·764	·757	·749	·741	·733	·725	·717	·708	·700	30
5 0	·875	·866	·858	·849	·840	·832	·823	·814	·805	·796	·787	·778	5 0
30	·962	·953	·943	·934	·924	·915	·905	·895	·885	·875	·865	·855	30
6 0	1·049	1·039	1·028	1·018	1·008	·997	·987	·976	·965	·955	·944	·933	6 0
30	1·136	1·125	1·114	1·103	1·091	1·080	1·069	1·057	1·045	1·034	1·022	1·010	30
7 0	1·223	1·211	1·199	1·187	1·175	1·163	1·150	1·138	1·125	1·113	1·100	1·087	7 0
30	1·310	1·297	1·284	1·272	1·259	1·245	1·232	1·219	1·205	1·192	1·178	1·165	30
8 0	1·397	1·383	1·370	1·356	1·342	1·328	1·314	1·300	1·285	1·271	1·256	1·242	8 0
30	1·484	1·469	1·455	1·440	1·425	1·410	1·395	1·380	1·365	1·350	1·334	1·319	30
9 0	1·570	1·555	1·539	1·524	1·508	1·493	1·477	1·461	1·445	1·428	1·412	1·396	9 0
30	1·657	1·640	1·624	1·608	1·591	1·575	1·558	1·541	1·524	1·507	1·490	1·473	30
10 0	1·743	1·726	1·709	1·692	1·674	1·657	1·639	1·621	1·603	1·586	1·568	1·549	10 0

Azimuth	LATITUDE												Azimuth
	54° 0′	54° 30′	55° 0′	55° 30′	56° 0′	56° 30′	57° 0′	57° 30′	58° 0′	58° 30′	59° 0′	59° 30′	60° 0′	
0° 30′	·077	·076	·075	·074	·073	·072	·071	·070	·069	·068	·067	·066	·065	30
1 0	·154	·152	·150	·148	·146	·145	·143	·141	·139	·137	·135	·133	·131	1 0
30	·231	·228	·225	·222	·220	·217	·214	·211	·208	·205	·202	·199	·196	30
2 0	·308	·304	·300	·297	·293	·289	·285	·281	·277	·274	·270	·266	·262	2 0
30	·385	·380	·375	·371	·366	·361	·356	·352	·347	·342	·337	·332	·327	30
3 0	·461	·456	·450	·445	·439	·433	·428	·422	·416	·410	·404	·398	·393	3 0
30	·538	·532	·525	·519	·512	·505	·499	·492	·485	·479	·472	·465	·458	30
4 0	·615	·608	·600	·593	·585	·578	·570	·562	·555	·547	·539	·531	·523	4 0
30	·692	·683	·675	·667	·658	·650	·641	·632	·624	·615	·606	·597	·588	30
5 0	·768	·759	·750	·741	·731	·722	·712	·702	·693	·683	·673	·664	·654	5 0
30	·845	·835	·825	·814	·804	·794	·783	·773	·762	·751	·741	·730	·719	30
6 0	·922	·911	·899	·888	·877	·865	·854	·843	·831	·819	·808	·796	·784	6 0
30	·998	·986	·974	·962	·950	·937	·925	·912	·900	·887	·875	·862	·849	30
7 0	1·074	1·062	1·049	1·035	1·022	1·009	·996	·982	·969	·955	·942	·928	·914	7 0
30	1·151	1·137	1·123	1·109	1·095	1·081	1·066	1·052	1·038	1·023	1·008	·994	·979	30
8 0	1·227	1·212	1·197	1·182	1·167	1·152	1·137	1·122	1·106	1·091	1·075	1·059	1·044	8 0
30	1·303	1·288	1·272	1·256	1·240	1·224	1·208	1·191	1·175	1·158	1·142	1·125	1·109	30
9 0	1·379	1·363	1·346	1·329	1·312	1·295	1·278	1·261	1·243	1·226	1·209	1·191	1·173	9 0
30	1·455	1·438	1·420	1·402	1·384	1·366	1·348	1·330	1·312	1·294	1·275	1·257	1·238	30
10 0	1·531	1·513	1·494	1·475	1·457	1·438	1·419	1·400	1·380	1·361	1·342	1·322	1·302	10 0